



Modelling Effects of Flow Withdrawal Scenarios on Riverine and Riparian Features of the Yampa River in Dinosaur National Monument



Downstream towards Mathers Hole, Yampa River, Dinosaur National Monument.

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Modelling effects of flow withdrawal scenarios on riverine and riparian features of the Yampa River in Dinosaur National Monument

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Abstract

The National Park Service (NPS) is charged with maintaining natural riverine resources and processes in its parks along the Yampa River and downstream along the Green River. This mission requires information on how proposed water withdrawals would affect resources. We present a methodology that quantifies the impact on natural riverine and riparian features of Dinosaur National Monument based on alternative withdrawals that vary in volume and timing. This methodology uses a reverse quantification and develops tools to enable the NPS to ensure that if withdrawals must occur, the adverse impacts would be minimized by prescribing or constraining the timing, magnitude, and duration of withdrawal. The reverse quantification, well-suited for unregulated rivers such as the Yampa, strives to protect all flows minus extractions from daily flows based on three parameters: 1) a minimum flow, below which water diversion does not occur; 2) the percentage of the flow above the minimum that is diverted; 3) the maximum daily flow that is diverted. We apply 350 flow extraction scenarios, each defined by a unique set of parameters, to the 99 historic annual hydrographs of daily flows (water year (WY) 1922–2020), and to the more recent 20 years (WY 2001–2020). We also consider how hydrologic year type (wet to dry) influences the flow volume extracted and impact to the resource. Recognizing the seasonal differences in flow and ecological and geomorphic response, we divide each year into four distinct seasonal periods and use relations from the literature between flow, channel change, riparian vegetation and fish behavior, physiology, and habitat to define hydrograph and resource metrics used to evaluate impacts to the resource. While our analysis demonstrates that all withdrawals will damage the resource, extractions during the Early Runoff Period (March 15 – April 30) are least detrimental and extractions during the Summer Baseflow Period (July 16 – October 31) are most detrimental. We find that most aspects of the resource are more sensitive to increasing extractions during drier years than during wetter years. Recent decades have seen a shift towards more frequent drier years, resulting in less water in most periods. As a result, our analysis suggests that extractions in recent decades would have had a greater impact on the resource when compared to similar extractions during the full historical record. Finally, we demonstrate how the NPS may use these results to develop limits on extractions for resource protection.

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Statement of Need

The Yampa River is the last lightly regulated large river remaining in the Colorado River Basin. Protecting the full spectrum of Yampa River flows is critical to maintaining river dependent resources throughout Yampa Canyon in Dinosaur National Monument (DINO) and downstream on the Green River from DINO to its confluence with the Colorado River in Canyonlands National Park (CANY). Large seasonal and interannual variability in flow and high sediment load support threatened and endangered fishes and are responsible for the broad, mobile, multi-thread, relatively unvegetated channel of the Yampa River, characteristics that have been lost on the other more heavily regulated rivers in the region (Scott and Friedman, 2018). The Yampa is also the most important source of high flows and sediment to the Green River downstream from Flaming Gorge Dam (LaGory *et al.*, 2019; Topping *et al.*, 2018). For these reasons protection of flows in the Yampa River is especially important. DINO and CANY protect long sections of the Yampa and Green rivers in Colorado and Utah. NPS is charged with maintaining natural riverine resources and processes for future generations including native fishes and vegetation, their riverine and riparian habitat, the river and channel themselves, and the recreational opportunities they provide. Faced with increasing competition for water in the Yampa River Basin and predicted future decreases in runoff, NPS needs quantitative information showing how changes in flow would affect resources.

This report provides information on the impacts of flow extractions on the resource of the Yampa River in DINO and lays out a flow prescription framework that can be used to minimize impacts. The next section (**The Hydrologic Regime of the Yampa River**) presents key information on the hydrologic regime of the Yampa River including changes that have occurred in the past century, the four seasonal periods that define intra-annual variation of the natural flow regime, and the influence of this variation on channel morphology and habitat for fish and riparian vegetation. In the **Flow Prescription Concept** section, we describe the flow prescription concept, which is based on a historical analysis of alternative extraction scenarios designed to maintain the natural variability of the Yampa River's hydrologic regime. The concept is built on the relationship between the volume of water extracted and the impact to the resource (i.e., geomorphology, native riparian vegetation, and native fishes). The resulting volume-impact relations are explored in the **Results and Interpretation** section for different sub-sets of the hydrologic record to understand how sensitive the resource is to water extractions, notably in the different seasonal periods, and how impacts may change in a future warmer, drier climate. The next section (**Application: Integrating Analyses into Decision Making**) presents a series of case studies that illustrate how the information provided in this report may be used as guidance for the NPS to evaluate how water development proposals may adversely affect NPS resources. The report concludes with a description of the limitations of the approach and additional considerations for NPS when evaluating water development proposals.

The Hydrologic Regime of the Yampa River

Historical Changes

The Yampa River is the least altered large river in the Colorado River Basin (Anderson and Stewart, 2007; Andrews, 1986). The wide, complex, and sparsely vegetated channel is maintained by annual snowmelt floods, the magnitude of which have not significantly changed in the 99-year record (Appendix A). Yet, more subtle changes to hydrology have occurred, notably in recent decades because of diversions and shifts to runoff patterns from a changing climate, that have affected the resource (Bestgen, 2015; Manners *et al.*, 2014). Table 1 compares monthly mean observed flows at Deerlodge Park for 1990–2019 to natural flows, which are estimates by the Bureau of Reclamation of the flows that would have occurred in the absence of existing diversions. On an annual basis, diversions remove about 12% of flow. Diverted volumes are greatest in June, July, and August, but the highest proportional depletions occur in August and September, when more than half of the flow that would naturally occur at Deerlodge Park is diverted. Therefore, although hydrologic effects of existing flow modifications are generally moderate, summer base flows have already been strongly reduced resulting in impacts to resources including reduced habitat for native fish and rising summer water temperature, which favors nonnative predator fish (Bestgen, 2015).

In the past 20 years, there has also been an increase in the frequency of drier years. Years classified as Wet or Moderately Wet have become 40% less common, whereas years classified as Dry or Moderately Dry have become 44% more common (see description of water year types in the next section). As a result of these drier conditions and flow diversions, there has been approximately 7% less volume annually in the Yampa River in the past 20 years (2001–2020) than in the previous 79 (1922–2000).

Table 1. Observed and reconstructed natural flows for water years 1990–2019 at Deerlodge Park, CO. Numbers listed in the table are monthly or annual mean values in cubic feet per second (cfs). Natural flows, calculated by the Bureau of Reclamation (<https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html>), are estimates of the flows that would have occurred without diversions. Natural and observed flows are both the sum of values reported for the Yampa River near Maybell, CO (USGS gage 09251000) and the Little Snake River near Lily, CO (USGS gage 09260000).

Category	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Observed	465	484	381	394	438	1198	3448	8176	6875	1530	345	289	2006
Natural	552	516	412	423	474	1233	3528	8557	7619	2311	951	616	2272
Observed/ Natural	0.84	0.94	0.92	0.93	0.92	0.97	0.98	0.96	0.9	0.66	0.36	0.47	0.88
Natural – Observed	87	32	31	29	36	35	79	381	745	781	606	323	266

Seasonal Variation in the Relation Between Discharge and Natural Resources

The effect of flow in the Yampa River on natural features protected by NPS varies seasonally. Runoff is dominated by snowmelt and peak flows occur in late spring or early summer, followed by much lower base flows in late summer, fall and winter. We divided the annual hydrograph into four hydrologically distinct periods, presented below, with different relations between functional flow components and riverine resources (Figure 1). For more information on functional flow components and their relationship to the natural resources of the Yampa River see Appendix B.

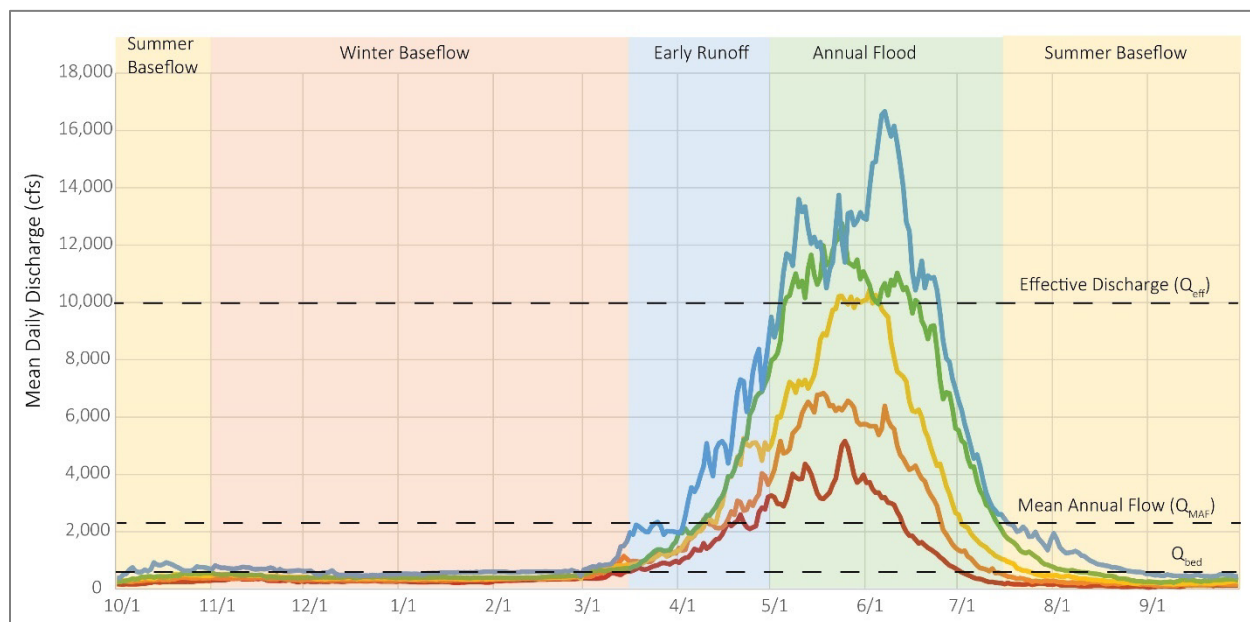


Figure 1. Annual hydrograph for the Yampa River, Colorado, USA broken into four hydrologically distinct seasonal periods: Winter Baseflow, Early Runoff, Annual Flood and Summer Baseflow. Median values of mean daily discharges (in cubic feet per second, cfs) are shown for the five hydrologic year types including Wet (blue line), Moderately Wet (green line), Average (yellow line), Moderately Dry (orange line), and Dry (red line). Dashed lines indicate important flow thresholds defined for hydrograph metrics used to quantify impacts to the resource for alternative extraction scenarios (see section on **Hydrograph and Resource Metrics**).

The **Winter Baseflow** Period extends from November 1 – March 14. Sufficient discharge during the Winter Baseflow Period maintains habitat depth, volume, and food availability for endangered and threatened fishes (Wick and Hawkins, 1989). Encroaching vegetation can be removed from the channel in winter by flow fluctuations, whose effects are magnified by formation and movement of ice (Johnson, 2000; Lind *et al.*, 2014; Smith and Pearce, 2000). On the other hand, large fluctuations in winter flow may disrupt habitat stability and create stressful conditions for fish (Bestgen, 2015).

The **Early Runoff** Period extends from March 15 – April 30. Flows generally increase during this period as temperatures rise and snow begins to melt. The moderately high flows in this period have some of the benefits described below for the Annual Flood period, but those benefits are usually

weaker during the Early Runoff Period because the flows are not as high, spawning of most fish has not begun, and vegetation is mostly dormant.

The **Annual Flood** Period extends from May 1 – July 15. The magnitude, duration, volume, timing, and interannual variability of the annual snowmelt pulse are important for maintaining NPS resources. Peak flows remove encroaching vegetation through erosion and extended inundation (Auble and Scott, 1998; Friedman and Auble, 1999), maintaining the habitat complexity necessary for threatened and endangered fishes (Pennock *et al.*, 2022) and creating the new surfaces necessary for establishment of native disturbance-dependent riparian vegetation (Scott *et al.*, 1996). High flows also are necessary to mobilize gravel and cobbles in Yampa Canyon and on tributary fans (Mussetter and Harvey, 1994; O'Brien, 1984) to form and flush spawning habitat (Tyus and Karp, 1989), and to refill floodplain wetlands necessary for rearing juvenile endangered fishes (Webber, 2013). Cumulatively, high flows during this period and the Early Runoff period determine the sediment mass balance (Topping *et al.*, 2018). Reduced flood magnitude and duration may lead to fine sediment accumulation on gravel bars and within secondary channels, decreasing channel capacity (Dean *et al.*, 2020). As temperatures rise during this period, maintaining higher flows buffers against rapid warming of water that increases invasive small-mouth bass growth rates (Anderson and Stewart, 2005). Maintaining natural timing of peak flows is important to promote migration and spawning of adult native fish, to disperse larval fish (Muth *et al.*, 2000) and to coincide with seed release of native riparian plants (Cooper *et al.*, 1999; Stella *et al.*, 2006). Large peaks in some years are necessary to maintain channel width and complexity. Multiple years in a row with similar flows promote encroachment of woody vegetation. Multiple consecutive years of low peaks can be especially damaging by allowing establishment and growth of vegetation on low bars (Alexander, 2007; Manners *et al.*, 2014; Walker *et al.*, 2020).

The **Summer Baseflow** Period extends from July 16 – October 31. As in the Winter Baseflow Period, sufficient discharge during summer baseflow maintains habitat depth, volume, and food availability (Bestgen *et al.*, 2006; Muth *et al.*, 2000). Summer baseflows have additional benefits, including preventing establishment of encroaching plants (Cooper *et al.*, 2003) and keeping water temperatures cool (Carveth *et al.*, 2006; Poole and Berman, 2001). Late summer base flows have already been reduced by water development more strongly than flows at any other time of year (see **Historical Changes** Section and Table 1).

Flow Prescription Concept

A flow prescription defines the flows necessary to maintain a riverine resource. Flow prescriptions typically quantify precise environmental flows at specific times (Poff and Matthews, 2013). This strategy is effective in rivers that are regulated by reservoirs, which can help to deliver those flows (LaGory *et al.*, 2019; Muth *et al.*, 2000). The Yampa River has no large reservoirs and is characterized by strong daily, seasonal, and interannual flow variability necessary for maintaining the broad, complex, rapidly migrating channel; healthy riparian vegetation communities; and populations of native fishes (Bestgen, 2015; Scott and Friedman, 2018). A traditional flow prescription would have two shortcomings on the Yampa. First, stipulating flows at specific times would remove much of the flow variability NPS seeks to protect. Second, because there is no large dam, there is no way to deliver those flows. Instead, our proposed flow prescription concept protects all of the flow each day minus a defined volume of water that is diverted. This approach of quantifying what is removed instead of what remains is known as a “reverse quantification”, an approach that protects flow variability in lightly regulated rivers while identifying a predictable amount of diverted water (Silk *et al.*, 2000). Any flow diversion will negatively impact the Yampa resource. The purpose of defining diverted flows is not to facilitate additional withdrawals from the Yampa River, but to ensure that if they must occur, their impacts are quantified and minimized. We determine diverted flow using three parameters: 1) a minimum flow, below which water diversion may not occur; 2) the percentage of the flow above the minimum that may be diverted; 3) the maximum daily flow that may be diverted. Daily diverted flows are calculated based on the mean annual flow of the day of the diversion.

Instead of defining thresholds in the quantity, timing, or frequency of flows which, when crossed, will harm the natural resources of the Yampa River, as a typical environmental flow assessment would do, we demonstrate how all extractions will have some adverse impact on physical and ecological processes that regulate the riverine resource protected by NPS. We quantify the degradation to the resource for increasingly greater extraction volumes. Unique flow extraction scenarios (i.e., different sets or combinations of the three parameters) are associated with a seasonal volume extracted and an adverse impact to the natural resources of the Yampa River. Impacts are defined based on how extractions alter functional flow components that support physical and ecological processes. Because different scenarios can result in similar extraction volumes, we identify those scenarios that minimize the impact to the resource for a given extraction. The optimized scenarios define volume-impact relations and serve as a framework from which the feasibility and impact of water development proposals may be evaluated. Because functional flow components vary among seasons, volume-impact relations are unique to each of the four seasonal periods. This allows exploration of how varying seasonality of withdrawal changes the associated impact.

Here we describe the methodology used to define volume-impact relations for the Yampa River (also see Appendix C). The approach relies on the assumption that the target condition of the Yampa River is represented by the annual and seasonal variability of the historical flow record. We evaluate how flow extraction scenarios would alter historical hydrographs, quantify the resulting changes using a

set of metrics of hydrograph change, and relate hydrograph changes to changes to the resource using published relations between flow, sediment transport, vegetation, and fish physiology, behavior, and habitat. Past flow extraction, especially in summer baseflows, has already impacted the resource (see section on **Historical Changes**). In addition, past climatic fluctuations have reduced both the interannual variability of flow in the Yampa River (Manners *et al.*, 2014) and the mean annual flow downstream in the Green River (Allred and Schmidt, 1999). Thus, what we present is an assessment of impacts of additional flow extraction on riverine resources in DINO. These impacts may be considered along with those of other factors influencing flow and riverine resources, such as climate change and introduction of non-native species. We analyze two versions of the hydrologic record: the 99-year hydrologic record, which represents the full range of flow variability; and the past 20 years, which have been drier than the rest of the record and may be more representative of future conditions. We also analyze the record by hydrologic year type (i.e., isolate the wettest years from the driest years) to understand how the natural variability in water availability affects the volume-impact relations.

Historical and Alternative Hydrographs

To evaluate the potential degradation to the resource with the extraction of water, we relied on the historical streamflow record for the Yampa River at Deerlodge Park, CO (USGS gage 09260050, Deerlodge Park). The Deerlodge Park stream gage has reported daily mean discharge since October 1, 1982, except for water years 1995 and 1996. We reconstructed the data for 1995 and 1996 and extended the record back to 1922 by summing the daily mean discharge at the Yampa River near Maybell, CO (USGS gage 09251000) and the Little Snake River near Lily, CO (USGS gage 09260000), consistent with other studies (Elliott *et al.*, 1984; Manners, 2013; O'Brien, 1984). The full record extended from 1922 to 2020, a total of 99 years. For each of the 99 years, we applied 350 flow extraction scenarios, each defined by a unique combination of extraction parameters (Table 2), resulting in 34,650 alternative hydrographs. In the extraction scenarios examined, percent extraction above the minimum flow ranged from 0.1% to 100%, and maximum flow extracted ranged from 25 cfs to 1000 cfs, broad ranges designed to capture a diversity of proposed diversions. The minimum flow below which new diversions are prevented was set to 300 cfs for all scenarios and seasons to assure fish passage through riffles, to prevent high temperatures that could strongly favor invasive fishes, and to prevent mortality of riparian forest from sudden lowering of the water table (Anderson & Stewart, 2005; Wick & Hawkins, 1989; Williams *et al.*, 2022), all serious impacts to the resource at DINO. Note that this minimum flow parameter prevents new extractions when flows are below 300 cfs but does not prevent flows from dropping below 300 cfs as a result of decreasing runoff or diversion under existing water rights. Although the flow prescription concept would allow varying the minimum flow by season, we chose not to do so because supporting evidence is not sufficient.

Because extraction scenarios have a very different impact on dry years vs wet years, water years were classified into one of five hydrologic year types based on historical flow volumes for the full 99-year record. Dry years were exceeded more than 90% of the time, Moderately Dry years were exceeded between 90% and 70% of the time, Average years were exceeded between 70% and 30% of the time, Moderately Wet years were exceeded between 30 and 10% of the time, and Wet years were exceeded less than 10% of the time. This assignment of year types follows the approach currently

used along the Green River (LaGory *et al.*, 2019). We note that the past 20 years of the 99-year record have shifted towards drier conditions. Wet and Moderately Wet years have become 40% less common, while Dry and Moderately Dry years are 44% more common in the past 20 years relative to the previous 79 years.

Table 2. Range of flow extraction parameters used to define the 350 scenarios applied to the 99-year historical record of the Yampa River to create volume-impact relations. Each scenario represents a unique combination of parameters (e.g., minimum flow of 300 cfs, 30% extraction above minimum, and 500 cfs maximum flow extracted).

Extraction Parameter	Range of Values for Alternative Analysis	
	Minimum	Maximum
Minimum Flow	300 cfs	300 cfs
% Extraction Above Minimum	0.1%	100%
Maximum Flow Extracted	25 cfs	1000 cfs

Extracted Volume

For each of the 34,650 alternative hydrographs and each of the four seasonal periods, an extracted volume was calculated as the difference in total volume between the historical and alternative hydrographs. The extracted volume is the amount of water diverted in a particular year and seasonal period, given the specified flow extraction parameters. Because the periods vary in duration, we also calculated the average daily extraction rate. The total extracted volume (in acre-feet, AF) and associated average extraction rate (AF Day⁻¹) were defined as:

$$\text{Extracted Volume (AF)} = \sum_{i=1}^n (Q_{\text{historical}} - Q_{\text{alternative}}) \times 1.98$$

$$\text{Extraction Rate (AF day}^{-1}\text{)} = \frac{1}{n} \sum_{i=1}^n (Q_{\text{historical}} - Q_{\text{alternative}}) \times 1.98$$

where $Q_{\text{historical}}$ is the mean daily flow for a given period in a given year (cfs), $Q_{\text{alternative}}$ is the mean daily flow under a given alternative (cfs), n is the number of days in the period, and 1.98 is the conversion between mean daily discharge (cfs Day⁻¹) and AF.

Hydrograph and Resource Metrics

All flow diversions impact the resource, adding to effects of diversions that have already occurred in the past. To quantify the impact to the resource for each of the 350 alternatives, we defined six hydrograph metrics, each related to a unique resource metric (Table 3). Hydrograph metrics measure the change to functional flow components relative to the historical hydrograph. Resource metrics translate the changes to the hydrograph to a change in geomorphic processes, the vegetation community, or native fishes relative to the target condition. Resource metric definitions are based on

published relationships between functional flow attributes and the geomorphic, vegetative, or native fishery response. Where there has not been a quantitative relationship developed for a given metric, we described the proportional change to the resource metric based on a proportional change to the hydrograph metric using our best judgement. Effects of water extraction on the resource vary seasonally, and we calculated a hydrograph and resource metric only for those seasonal periods in which it was relevant (Table 3). Hydrograph and resource metrics were calculated for each year in the 99-year historical record and range from 0 (no impact, or in other words no difference between alternative and historical condition) to 1 (100% difference between alternative and historical condition).

Below we define each of the six hydrograph and resource metrics and describe how resource metrics are derived from hydrograph metrics. All hydrograph and resource metrics are listed in Table 3, and additional information on analyses used to define the resource metrics is presented in Appendix D.

Table 3. Range of flow extraction parameters used to define the 350 scenarios applied to the 99-year historical record of the Yampa River to create volume-impact relations. Each scenario represents a unique combination of parameters (e.g., minimum flow of 300 cfs, 30% extraction above minimum, and 500 cfs maximum flow extracted).

Resource Metric	Hydrograph Metric	Hydrograph Metric Definition ^A	Seasonal Periods
Fish Habitat Availability. Provide sufficient depth through riffles for foraging and fish passage	Bed Coverage	$Q_{\text{alternative}} < Q_{\text{bed}} \ \& \ Q_{\text{historical}} < Q_{\text{bed}}, \ \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{historical}}(i) - Q_{\text{alternative}}(i)}{Q_{\text{historical}}(i)}$ $Q_{\text{alternative}} > Q_{\text{bed}} \ \& \ Q_{\text{historical}} > Q_{\text{bed}}, \ 0$ $Q_{\text{alternative}} < Q_{\text{bed}} \ \& \ Q_{\text{historical}} > Q_{\text{bed}}, \ \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{bed}} - Q_{\text{alternative}}(i)}{Q_{\text{bed}}}$	All
Plant Establishment. Reduce plant establishment by limiting exposure of channel bars	Bar Coverage	$Q_{\text{alternative}} < Q_{\text{MAF}} \ \& \ Q_{\text{historical}} < Q_{\text{MAF}}, \ \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{historical}}(i) - Q_{\text{alternative}}(i)}{Q_{\text{historical}}(i)}$ $Q_{\text{alternative}} > Q_{\text{MAF}} \ \& \ Q_{\text{historical}} > Q_{\text{MAF}}, \ 0$ $Q_{\text{alternative}} < Q_{\text{MAF}} \ \& \ Q_{\text{historical}} > Q_{\text{MAF}}, \ \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{MAF}} - Q_{\text{alternative}}(i)}{Q_{\text{MAF}}}$	Annual Flood, Summer Baseflow
Water Temperature. Maintain water temperatures below 30°C to prevent stress to native fish	Seasonal Average	$\frac{\frac{1}{n} \sum_{i=1}^n Q_{\text{historical}}(i) - \frac{1}{n} \sum_{i=1}^n Q_{\text{alternative}}(i)}{\frac{1}{n} \sum_{i=1}^n Q_{\text{historical}}(i)}$	Summer Baseflow
Sediment Load. Transport sediment long enough to deplete the annual supply	Flood Volume	$Q_{\text{historical}} > Q_{\text{MAF}}, \ \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{historical}}(i) - Q_{\text{alternative}}(i)}{Q_{\text{historical}}(i)}$ $Q_{\text{historical}} < Q_{\text{MAF}}, \ 0$	Early Runoff, Annual Flood
Geomorphic Work. Transport fine sediment and cross geomorphic thresholds to mobilize bed and erode banks	Flood Duration	$Q_{\text{historical}} > Q_{\text{eff}}, \ \frac{1}{n} \sum_{i=1}^n \frac{\#Q_{\text{historical}}(i) - \#Q_{\text{alternative}}(i)}{\#Q_{\text{historical}}(i)}$ $Q_{\text{historical}} < Q_{\text{eff}}, \ 0$	Early Runoff, Annual Flood
Channel Width. Minimize channel narrowing and maintain complex morphology.	Flood Peak	$\frac{\text{Peak}Q_{\text{historical}} - \text{Peak}Q_{\text{alternative}}}{\text{Peak}Q_{\text{historical}}}$	Annual Flood

^A $Q_{\text{historical}}$ is the mean daily discharge for historical hydrograph, $Q_{\text{alternative}}$ is the mean daily discharge with prescribed extractions for alternative scenario, Q_{bed} is the discharge determined to just cover the bed at the USGS gage at Deerlodge Park and is set to 600 cfs, Q_{MAF} is the mean annual flow for the reconstructed record at the USGS gage at Deerlodge Park and is set to 2,040 cfs, Q_{eff} is the estimated effective discharge and is set to 10,000 cfs, $\text{Peak}Q_{\text{historical}}$ is the annual peak discharge for the historical record, and $\text{Peak}Q_{\text{alternative}}$ is the annual peak discharge with prescribed extractions for a given alternative scenario.

Resource Metric: Fish Habitat Availability, Hydrograph Metric: Bed Coverage

Lower flows reduce overall habitat depth and area, reduce food availability, and limit fish passage. Riffles, in particular, are important areas of food production and foraging for all native fishes and are sensitive to reductions in base flows (Anderson and Stewart, 2005; Modde *et al.*, 1999; Wick and Hawkins, 1989). Incomplete coverage of riffles reduces habitat availability for fishes (Bestgen, 2015). To measure the impact to fish habitat availability, we defined the Bed Coverage hydrograph metric, which measures how flows below 600 cfs change between the historic and alternative hydrograph (Table 3). To determine this threshold, we looked to the USGS stream gage in Deerlodge Park and identified a transition in the relationship between stage and discharge around 600 cfs, from increasing flow width faster than depth to increasing depth faster than width (Appendix D). This transition was interpreted as the point when flows have covered the bed. Examination of aerial images captured at various flows in both Deerlodge Park and Yampa Canyon confirmed that this is an appropriate flow to use as a threshold for bed coverage. As exposure of the riffle is understood to be directly related to habitat availability, the Fish Habitat Availability resource metric is then defined similarly to the Bed Coverage hydrograph metric, as proportional change to flows below 600 cfs.

Resource Metric: Plant Establishment, Hydrograph Metric: Bar Coverage

Exposure of sand and cobble bars adjacent to the channel bed during the growing season provides opportunities for vegetation to establish and thrive, especially if lower flows persist over multiple years (Scott and Friedman, 2018). Submergence of these bars can help to prevent encroachment of riparian vegetation into the active channel, which could lead to channel simplification and degradation of habitat for native fishes (Friedman *et al.*, 1998; Scott and Friedman, 2018). We estimated the flow threshold representing the lower limit of perennial vegetation along the Yampa River. This estimate is derived from a field study documenting the germination elevation of 55 tamarisk (*Tamarix* spp.) plants in the Yampa Canyon (Manners *et al.*, 2014), repeat satellite images documenting the exposure of unvegetated bars, and preliminary analyses of long-term monitoring data. These data sources suggest that the mean annual flow (Q_{MAF}) approximates flows below which bars lack perennial vegetation. Thus, we defined the Bar Coverage hydrograph metric as a measure of the decrease in flows below Q_{MAF} , or 2040 cfs (Table 3). Because perennial plants require two or more years to become established, we defined the Plant Establishment resource metric as the minimum value of the given and previous year's hydrograph metric, highlighting the importance of flow sequencing on plant establishment and survival (Scott and Friedman, 2018).

Resource Metric: Water Temperature, Hydrograph Metric: Seasonal Average

Decreased streamflows influence water temperatures during the warm seasons (Poole & Berman, 2001), disrupting adaptations for reproduction and spawning of native fishes (Bestgen and Williams, 1994; Bestgen *et al.*, 1998; Muth *et al.*, 2000), enhancing growth rates of non-native species (Anderson and Stewart, 2005; Bestgen *et al.*, 2007), and potentially limiting habitat ranges (Fraser *et al.*, 2019). When water temperatures are elevated above approximately 30°C, over many days, native fishes may become significantly stressed (Carveth *et al.*, 2006). For the recent record of water temperatures measured by the USGS at the Deerlodge Park gage (2003–2022), a relationship exists between Summer Baseflow Seasonal Average discharge and the number of days temperatures exceed 30°C during that season. When Seasonal Average discharge exceeds 600 cfs, water temperatures

remain below 30°C for the whole season. With decreasing seasonal averages below 600 cfs, the number of days when water temperatures exceed 30°C increases (Appendix D). To capture this relationship between temperature and discharge, we calculated the Seasonal Average discharge during the Summer Baseflow period for the historical and alternative hydrographs. The Seasonal Average hydrograph metric represents the proportional change to this average (Table 3). The Water Temperature resource metric was then calculated as the proportional change in likely number of days to the historical condition. Because daily water temperature data do not exist for the full record, we used the relationship between Seasonal Average discharge and number of days temperatures exceed 30°C to estimate both the historical and alternative condition. The Water Temperature resource metric was calculated as the proportional change to the historical condition.

Resource Metric: Sediment Load, Hydrograph Metric: Flood Volume

Most sediment transport occurs at high flows. The volume of the snowmelt flood, defined as the cumulative volume of flows larger than the mean annual flow (Q_{MAF} ; 2,040 cfs), is a measure of the capacity to transport the fine sediment (especially sand) delivered from upstream. If flow volume is too small, the sand supply may not be moved through the reach, and deposition of bars in the channel may result, contributing to channel narrowing and cross-section simplification (Dean *et al.*, 2020; Elliott and Anders, 2005; Leonard, 2022). The Flood Volume hydrograph metric was calculated as the decrease in flood volume: in other words, the difference in volume of flows above mean annual flow between the historic and alternative flows (Table 3). To translate the hydrograph metric to a resource metric, we used the Elliott and Anders (2005) relation at Deerlodge Park to estimate daily sediment load from daily discharge above Q_{MAF} and summed the sediment load across an entire season. We then related this cumulative sediment transport to the volume of the snowmelt flood. The Sediment Load resource metric is the proportional change to the sediment load based on this relation. Because this relation differed between the Early Runoff and Annual Flood seasons, we calculated the resource metric separately for each season. While this resource metric captures the influence of flow on sediment load at Deerlodge Park, sediment load is also strongly influenced by the supply from upstream, which is controlled by the occurrence of local floods and land management in erosive tributary basins, especially in the Little Snake River Watershed (Kemper *et al.*, 2022; Topping *et al.*, 2018).

Resource Metric: Geomorphic Work, Hydrograph Metric: Flood Duration

Most geomorphic work is accomplished by the highest flows. The increment of discharge that transports the greatest fraction of the annual load is termed the effective discharge (Andrews, 1980). These larger flows are also critical for transporting and rebuilding the coarse streambed (Mussetter and Harvey, 1994; O'Brien, 1984). Reductions in the duration of the snowmelt flood above the effective discharge will limit mobilization of the bed, reducing channel mobility and the quality of spawning habitat (Wilcock and McArdell, 1997). The effective discharge for the Yampa River at Deerlodge Park has been estimated by E. Mueller (Utah State University, written personal communication, May 15, 2019) at 10,000 cfs. This is consistent with a value of 9,110 cfs calculated for the Yampa River upstream at Maybell, Colorado (Andrews, 1980). The Flood Duration hydrograph metric was quantified as the change to the number of days that mean daily flow exceeds 10,000 cfs between the alternative and historical hydrographs, relative to the number of days mean

daily flow exceeded 10,000 cfs in the historical hydrograph (Table 3). Because the impact to these flows is understood to be directly related to geomorphic work, the Geomorphic Work resource metric is then equal to the Flood Duration hydrograph metric.

Resource Metric: Channel Width, Hydrograph Metric: Flood Peak

Channel width scales to flood magnitude based on the general form $Q^{0.5}$ (Leopold and Maddock, 1953). Grams et al. (2020) demonstrated that this simple hydraulic-geometry based assessment described decadal-scale narrowing episodes along the Green River, Utah. Reduced peak flows allow establishment of vegetation within backwaters and secondary channels, leading to sediment deposition, channel narrowing and habitat degradation for native fishes (Grams et al., 2020). On the Yampa River and elsewhere in the Colorado River Basin, channel narrowing episodes disproportionately influence wider, multi-thread settings, resulting in narrower and simpler channels (Manners *et al.*, 2014; Van Steeter and Pitlick, 1998). To assess changes to channel width, the Flood Peak hydrograph metric was quantified as the change to flood peak magnitude for the alternative relative to the historical peak (Table 3). For each year, we then calculated the proportional change to channel width using the simple hydraulic geometry relationship.

Impact to the Resource

We calculated the impact to the resource for each seasonal period as the sum of all applicable resource metrics (Table 3). The impact to the resource during the Summer baseflow is the sum of Fish Habitat Availability, Plant Establishment, and Water Temperature and the impact to the resource during the Winter Baseflow period is the resource metric Fish Habitat Availability. For the Early Runoff period, the impact is the sum of the resource metrics for Fish Habitat Availability, Sediment Load, and Geomorphic Work. For the Annual Flood period the impact is the sum of Fish Habitat Availability, Plant Establishment, Sediment Load, Geomorphic Work, and Channel Width. Each resource metric varies between 0 (no change) and 1 (100% change from historical condition). As a result, the total impact could be greater than 1 and cannot be interpreted as a proportional change to the historical condition. Nevertheless, total impact values are useful for comparing relative impacts of alternative scenarios.

Generating Optimized Volume-Impact Relations

We calculated the extracted volume and impact to the resource for each of the 350 flow extraction scenarios applied to the 99 years in the four seasonal periods. We then used the volume extracted and impact to the resource for each scenario to perform a cost-benefit analysis on the system, evaluating how to minimize the impact for a given extraction. Because mean daily flows and total flow volume vary within and between years, a given scenario had a substantial range in seasonal extracted volume and impact through the historical record, and therefore likely into the future. We summarized the historical variability to identify representative values of volume and impact for each scenario and seasonal period using three different assessments described below. The assessments examine different portions of the historical record. We note that the first two assessments are used to develop management tools further described in the section on **Application: Integrating Analyses into Decision Making**, while the third is for better understanding variability in extracted water and resource impact between years.

Within an assessment, and for a given seasonal period, there were often similar extracted volumes for multiple scenarios but with different impacts (see section on **An Example Illustrating the Methodology**). For example, during the Summer Baseflow period for Assessment #1, there was approximately 60 AF Day⁻¹ diverted for both the scenario that extracts 80% of the flow above 300 cfs, not to exceed 150 cfs, and the scenario that extracts 50% of the flow above 300 cfs, not to exceed 750 cfs. However, the impact was 21% greater for the latter alternative. To develop tools to identify how to minimize impacts to the resource, we identified the scenario with the lowest impact for a given extracted volume. The selected scenarios defined the optimized volume-impact relation. The analyses based on the full gage record with no separation of year types (Assessment #1), and the analysis focused on the most recent 20 years (Assessment #2), each yielded a single optimized volume-impact relation for each seasonal period. The analysis parsing the historical record by year type (Assessment #3) yielded a unique optimized volume-impact relation for each seasonal period in each year type.

Assessment #1. Conservative Assessment of the Full Record

For the full historical record, we took a conservative approach, identifying extracted volumes that were exceeded 75% of the time for a scenario, and impacts that were exceeded in severity only 5% of the time for a given scenario. In other words, we identified the years that optimize volume based on the 25th percentile and minimize impact based on the 95th percentile (Fig. 2A & B) to represent the volume and impact for a scenario within a seasonal period. To get the 95th percentile total impact, we added up the 95th percentile impacts of all applicable resource metrics for that period. For the Summer Baseflow period, for example, the 95th percentile total resource impact was the sum of the 95th percentile impacts for Fish Habitat Availability, Plant Establishment, and Water Temperature. The choice of these percentiles is conservative for both park managers and water managers because for any given scenario it focuses attention on some of the worst (95th percentile) impacts and lowest (25th percentile) volumes of water extracted. We note that the choice of 25th and 95th percentiles as target values for extracted volume and impact, respectively, is meant to be representative and does not suggest an acceptable level of extraction or impact. Other target values could be used to represent the range of variation in a scenario.

Assessment #2. Conservative Assessment of the Most Recent 20 Years

For the most recent 20 years of the record (2001–2020), we took a similar approach as described above for the full record. We identified the extracted volume that was exceeded 75% of the time (i.e., the 25th percentile) during the past 20 years, and the impact exceeded 5% of the time. The focus on the most recent 20 years allows us to better capture recent low flows from summer withdrawals and increased prevalence of drier years, which are likely to become more common as a result of climate change.

Assessment #3. Assessment Subdivided by Year Type

To explore the effect of annually available water on impact to resources and extracted volume we subdivided the 99 years in the full hydrologic record into five year-types: dry, moderately dry, average, moderately wet, and wet and carried out the analysis by year type. Within year types, the analysis followed the procedure of Assessment #1 except that the representative extracted volume

and total impact were the mean for all years in the year type. Assessment #3 yielded a unique optimized volume-impact relation for each seasonal period in each year type.

An Example Illustrating the Methodology

The methodology described in the above sections is shown schematically in Appendix C and described in this section using an example to illustrate the process (Figure 2). We applied a scenario to the historical record to calculate the extracted volume and total impact for each year and seasonal period, identified a representative extracted volume and impact for each scenario and period, and built optimized volume-impact relations. Note that the example shown in Figure 2 is for the full historical record, Assessment #1, but the procedure would apply similarly to Assessment #2 (but for only the more recent 20 years) and Assessment #3 (isolating only those years classified in each of the five water year types). In Figures 2A and 2B we use the example of the scenario that extracts 30% of flows that exceed a minimum flow of 300 cfs, but not to exceed 100 cfs, applied to the Summer Baseflow period. For each year in the hydrological flow record, we quantified the change to the three hydrograph and resource metrics applicable to the Summer Baseflow period (Table 3, Figure 2A). Each resource metric was then ranked by increasing change to the resource relative to the historical condition. Because there are 99 years in the record, this ranking also corresponds with the percentile. The sum of the resource metrics in ranked order provides us with the total impact value, shown as the black dots in Figure 2A. The extracted volume was calculated as the difference in flow volume between the historical hydrograph and the alternative hydrograph, or the black and gray lines in the inset hydrograph in Figure 2B. In Figure 2B, years were ranked by increasing volume extracted (in AF Day⁻¹). Impact and volume distributions for the historical flow record shown in Figures 2A and 2B were used to identify the 95th percentile impact (or impact that is exceeded 5% of the time, Figure 2A) and the 25th percentile volume (or extracted volume that is exceeded 75% of the time, Figure 2B). The same exercise was carried out for the remaining scenarios during the Summer Baseflow period (black dots in Figure 2C). Scenarios that minimize the impact for a given binned volume define the optimized volume impact relation (yellow circles in Figure 2C). We used bins to define the lower envelope of the volume-impact relation and for use in the Extraction Lookup Table (Diehl, 2024). For extracted volumes less than 1 AF Day⁻¹, values were binned in 0.1 AF Day⁻¹ increments; for extracted volumes between 1 and 10 AF Day⁻¹, values were binned in 1 AF Day⁻¹ increments; for extracted volumes between 10 and 100 AF Day⁻¹, values were binned in 10 AF Day⁻¹ increments; for extracted volumes between 100 and 1000 AF Day⁻¹, values were binned in 25 AF Day⁻¹ increments; and for extracted volumes greater than 1000 AF Day⁻¹, values were binned in 50 AF Day⁻¹ increments.

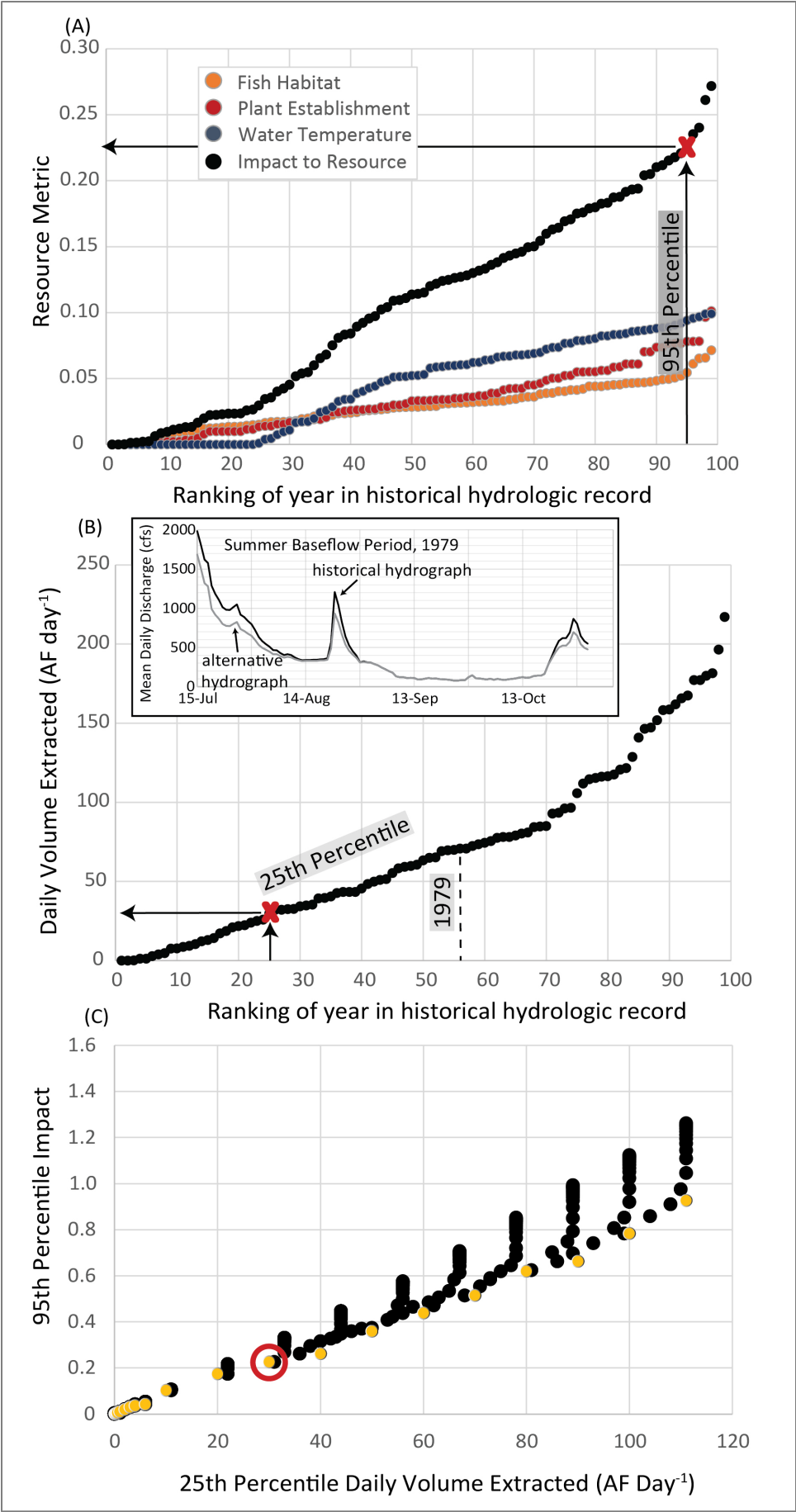


Figure 2. Development of the optimized volume-impact relations. Example shown is for the Summer Baseflow period. (A) Resource metrics (colored dots) for an example scenario (30% extraction above minimum flows of 300 cfs, maximum extraction of 100 cfs) applied to all years ranked by increasing values. Impact to the resource (black dots) represents the sum of all resource metrics and the red “x” marks the 95th percentile of the impact (0.227). (B) Volume extracted for the example scenario applied to all years and ranked by volume extracted. The red “x” marks the 25th percentile of volume extracted (~30 AF Day⁻¹). Inset to (B) is the historical (black line) and alternative (gray line) hydrograph for the example scenario applied to the year 1979. The difference between the black and gray lines defines the volume extracted, shown as the dashed line. (C) Volume-impact relations for all scenarios applied to the Summer Baseflow period. The red circle highlights the example scenario illustrated in panels A and B, corresponding to a 25th percentile volume extracted and the 95th percentile impact. The yellow dots define the envelope curve showing the minimum (optimum) value of 95th percentile impact as a function of the 25th percentile volume extracted.

Results and Interpretation

In this section we present the results of the flow extraction alternative analysis used to quantify the degradation to the resource relative to the current condition for increasingly greater extraction volumes. We first explore the results of the full suite of 350 extraction scenarios, applied to the first assessment (the full historical record) to understand how extracted volumes and impacts respond to the different extraction parameters. We then focus on the subset of scenarios that minimize the impact of extracting a given volume of water and use these scenarios to define the optimized volume-impact relations for all three assessments. Volume-impact relations are compared between seasonal periods and across assessment types to understand how the sampled years and seasons influence their shape. From these patterns, we discuss how the sensitivity of resource impacts to increasing flow extractions is influenced by seasonal period, water year type, and climate change.

Results: Extraction Scenarios

Hydrograph and resource metrics varied between 3×10^{-5} and 1.0, suggesting that for the alternative scenarios evaluated, water extraction could change the hydrograph and an individual resource by 100% compared to the current condition (Table 4 and Appendix E). Resource metrics typically tracked with hydrograph metrics, as the relationship between the two is largely linear (Appendix D). The numbers presented in Table 4, Appendix D and Appendix E represent the 95th percentile of the hydrograph and resource metrics for any alternative scenario.

Table 4. Range of hydrograph and resource metrics for the 350 extraction scenarios evaluated. Values represent the 95th percentile value, or the metric for which only 5% of the years had a greater change to the hydrograph or resource. The largest values were associated with scenarios that had high percent extractions and maximum flow extracted, but the effect of increasing either parameter varied for each of the metrics (Appendix E).

Resource Metric	Range	Hydrograph Metric	Range
Fish Habitat Availability	0.00003–0.46	Bed Coverage	0.00003–0.46
Plant Establishment	0.0001–0.40	Bar Coverage	0.0002–0.54
Water Temperature	0.0005–0.48	Seasonal Average	0.0008–0.56
Sediment Load	0.0007–0.19	Flood Volume	0.0009–0.27
Geomorphic Work	0.03–1.0	Flood Duration	0.03–1.0
Channel Width	0.0005–0.08	Flood Peak	0.001–0.14

The Flood Duration hydrograph metric and associated Geomorphic Work resource metric had the largest range of values (0.03 to 1.0; Table 4 and Appendix D and E) because the definition of the hydrograph metric was based on a threshold in the number of days flows exceeded 10,000 cfs. There were years in which no flows exceeded this threshold, and as a result, all scenarios resulted in an impact of “0”. However, there were also years in which the highest flows were just above the threshold and many of the extraction scenarios shifted those flows below the threshold, resulting in an impact of “1”. Bed Coverage, Bar Coverage, and Seasonal Average hydrograph metrics ranged

from very low values (i.e., less than 0.001) to ~0.50, and their associated resource metrics had similar ranges, from less than 0.001 to ~0.45 (Table 4 and Appendix D). The Flood Peak hydrograph metric had the smallest range (0.001 to 0.14) of all the metrics, as did its associated resource metric, Channel Width (<0.001 to 0.08). Because flood peak magnitude is large, the proportional change to its value is small, and as a result the hydrograph and resource metrics are relatively small, but these small metrics are meaningful and likely to reflect other more complex processes (see section on **Conclusions and Additional Considerations**). It would be possible to weigh resource impacts depending on their relative importance for specific purposes, but we have not done so here to minimize complexity and subjectivity.

Hydrograph and resource metrics applicable to multiple seasonal periods varied in their magnitude between periods but retained relatively similar response surfaces to different extraction scenarios (Appendix D). Fish Habitat Availability, associated with the Bed Coverage hydrograph metric, was greatest in the baseflow periods, notably in the Winter Baseflow, but minimal during the Annual Flood (Appendix E). Similarly, Plant Establishment, associated with the Bar Coverage hydrograph metric, had a greater range of values in the Summer Baseflow period than the Annual Flood. The resource metrics responded to the extraction scenarios differently, based on whether the resource metric relied on a hydrograph metric that measured changes to lower flows (i.e., Bed Coverage, Bar Coverage, Seasonal Average) or higher flows (i.e., Flood Volume, Flood Duration, Flood Peak). Fish Habitat Availability, Plant Establishment, and Water Temperature were more sensitive to the percent of flows extracted than to the maximum flow extracted. In contrast, the Sediment Load, Geomorphic Work, and Channel Width resource metrics were most sensitive to the maximum flow extracted, and only minimally impacted by a shift to the percent of flows. We further explore the trends in the resource metrics in the section on **Results: Volume-Impact Relations**.

Total impact to the resource had the greatest range in values for the Summer Baseflow and Annual Flood periods (Table 5). Maximum impacts during the Winter Baseflow and Early Runoff periods were much smaller. The volume extracted for the range of 350 scenarios was greatest in the Early Runoff and Annual Flood periods and an order of magnitude less during the Summer and Winter Baseflow Periods (Table 5).

Table 5. Range of volume extracted and impacts to the resource for the 350 extraction scenarios. Impact values represent the 95th percentile value for a given scenario, whereas volumes extracted represent the 25th percentile value for a given scenario. The largest values were associated with scenarios whose parameters included high percent extractions and maximum flow extracted, but the effect of increasing either parameter varied for each of the metrics (Appendix E).

Hydrograph Period	Volume Extracted (AF Day ⁻¹)	Impact to Resource
Summer Baseflow	0.1–111	0.001–1.26
Winter Baseflow	0.1–116	0.0003–0.46
Early Runoff	3–1596	0.0008–0.53
Annual Flood	9–1842	0.03–1.54

Extracted volumes during the runoff periods (Early Runoff and Annual Flood) were more sensitive to scenarios that increased the maximum flow extracted than the percent extracted above a minimum threshold (Figure 3), whereas extracted volumes during the baseflow periods (Summer and Winter Baseflow) were more sensitive to the percent of water above a minimum threshold. Trends in the response surfaces of the impact to the resource (right panel in Figure 3) for the baseflow periods generally mirrored the trends in metrics associated with low flows (Appendix E). On the other hand, the impacts to the runoff periods reflect a mix of low and high flow metrics. Additionally, the contours on the impact surfaces for the Annual Flood period are not as smooth as they are on the other surfaces, reflecting the influence of thresholds within the Geomorphic Work resource metric.

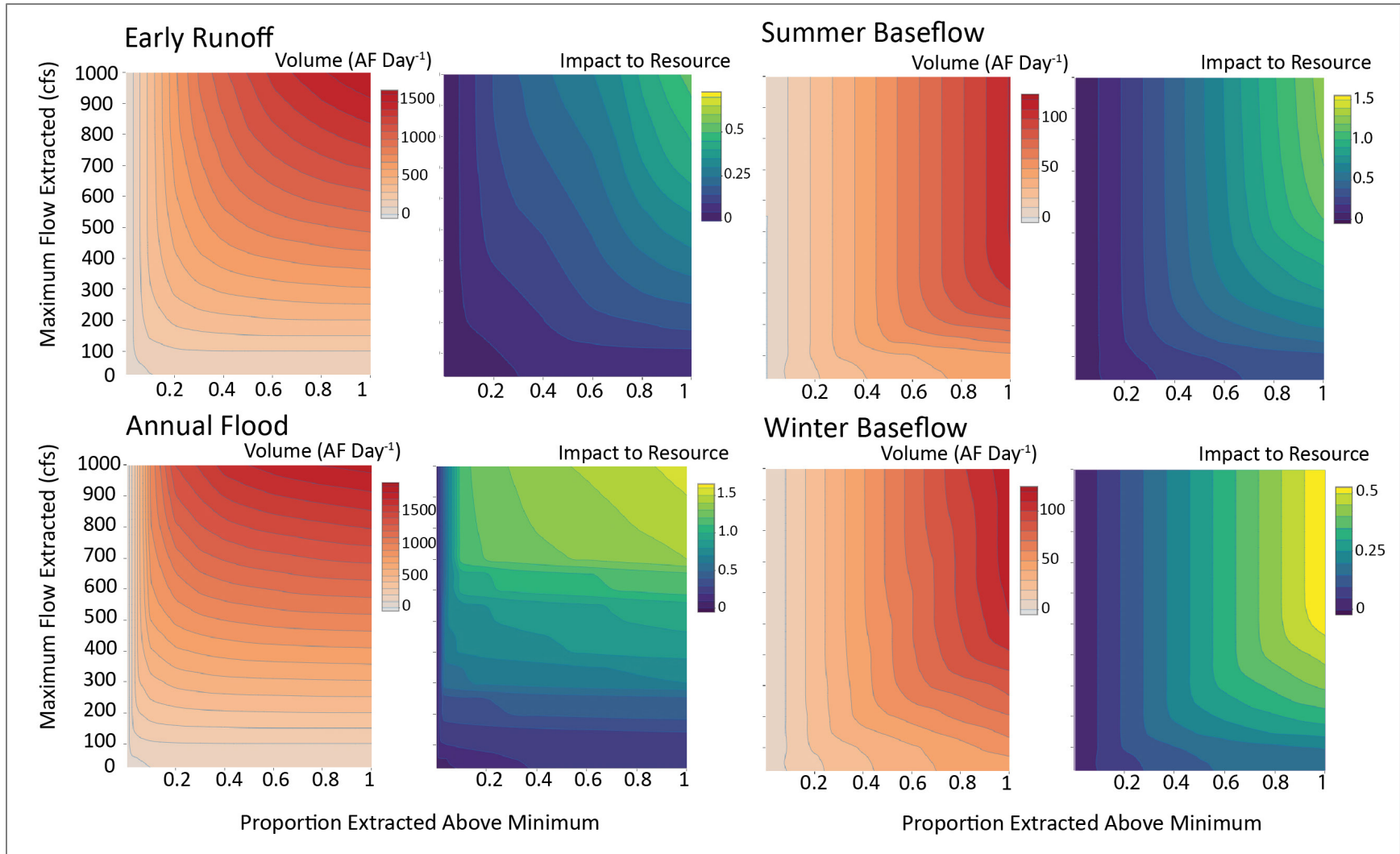


Figure 3. Response surfaces of flow volume extracted (AF Day⁻¹) and impact to the resource for the 350 extraction scenarios evaluated in this analysis, which varied based on the percent extracted above a minimum threshold of 300 cfs (x-axis) and the maximum flow extracted (y-axis). Note that the scale of the response variable differs between seasonal periods.

Results: Volume-Impact Relations

We identified the optimized volume-impact relation for each of the four seasonal periods by minimizing the impact to the resource for a given binned value of daily volume extracted associated with each extraction scenario. Figure 4 shows the relationship between volume-impact pairs for the 350 scenarios (black dots) and the scenarios representing the optimized volume-impact relation (colored dots) for the full record (i.e., Assessment #1).

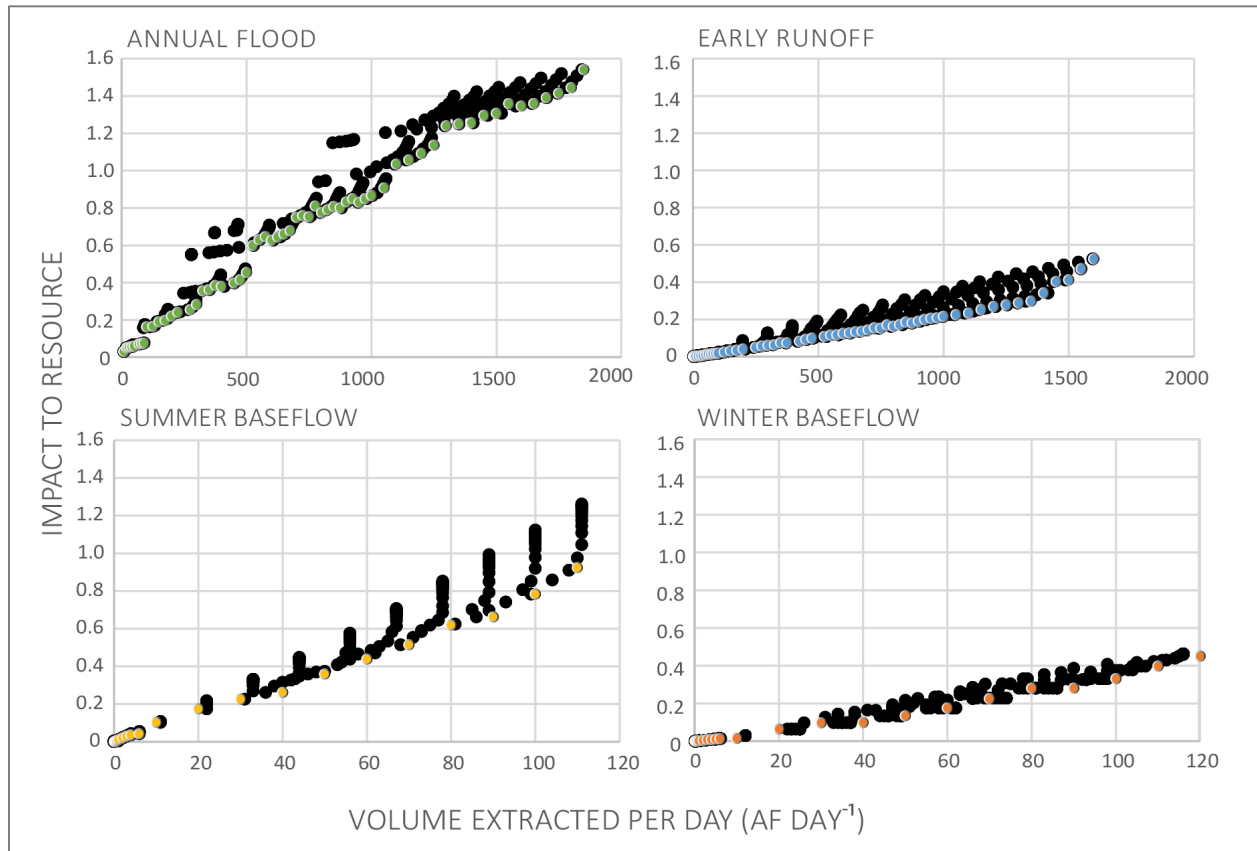


Figure 4. Volume-impact pairs for 350 scenarios (black dots) for each of the four seasonal periods identified based on the 95th percentile impact to the resource within a given scenario and the 25th percentile volume extracted. Colored dots indicate the scenarios that minimize the impact to the resource for a given daily volume extracted. The data shown here is for the full 99-year record (Assessment #1). Colored dots in this figure are the same as those in Figure 5A. Yellow dots are the same as those in Figure 2C.

Figure 5 shows the optimized volume-impact relations for the full hydrologic record (Assessment #1; Figure 5A) and the most recent 20 years (Assessment #2; Figure 5B) based on total extracted water normalized by the duration of the period in AF Day⁻¹, along with the inter-quartile range of volume extracted for each scenario identified. The volume-impact relations for the full hydrologic record and the more recent years depicted in Figure 5 are also summarized in tabular form in the Extraction Lookup Table (Diehl, 2024). The Extraction Lookup Table is organized by seasonal period, for increasing extraction rates (AF Day⁻¹), and reports on the variability in both potential extraction

volumes and daily rates and impacts to the hydrograph and resource that may occur based on the historical record. Columns and rows are clearly labeled within the Extraction Lookup Table to facilitate the discussion of results and the integration of the results into decision making applications (see section on **Application: Integrating Analyses into Decision Making**).

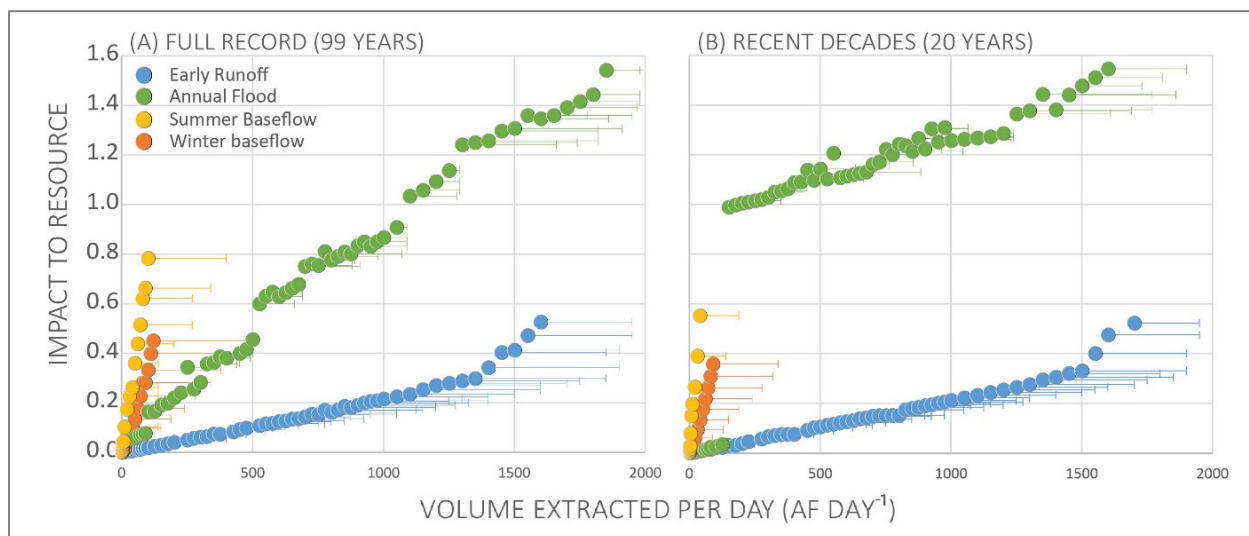


Figure 5. Optimized volume-impact relations using the total volume extracted per day (AF Day⁻¹), for (A) the full hydrologic record (Assessment #1) and (B) the two more recent decades (Assessment #2). For each of the four periods, the 25th percentile volume and 95th percentile impact to resource are used to identify the scenarios that minimize impact for a given volume of water. The inter-quartile range of water volume is also shown as a thin horizontal line. The range of data on the x axis is indicative of the maximum amount of water extracted, whereas the slope of the volume-impact relation reflects the sensitivity of the resource to increasing extractions.

The range of variation in each panel in Figures 4 and 5 is a function of the flow extraction scenarios evaluated, the seasonal period, and the number of years assessed. The Annual Flood and Early Runoff periods extend further to the right because discharges are higher in those periods than during the Summer and Winter Baseflow periods. As such, for the same assessment and extraction scenario, more water may be extracted from the Annual Flood and Early Runoff periods. The minimum flow of 300 cfs further limits the volume of water extracted during the baseflow periods, and therefore also puts a bound on the maximum impact quantified in this analysis. The Annual Flood had the most total extracted water and the Summer Baseflow period had the least. The maximum flow extraction scenario considered specified 100% removal of water above a minimum flow of 300 cfs, not to exceed 1000 cfs. Applied to the Annual Flood period for the full historical record (Assessment #1), we found that 75% of the time, approximately 138,750 AF, or 1,850 AF Day⁻¹, was extracted under these parameters (Extraction Lookup Table, Assessment #1, Row 123, Diehl, 2024). Conversely in the Summer Baseflow period, extraction was less than 1000 cfs on almost all days. In fact, flow extraction scenarios with maximum extraction of 450 cfs produced the same volumes of water as scenarios with a maximum extraction of 1000 cfs because the majority of mean daily discharges in the Summer Baseflow period are below 750 cfs (i.e., minimum flow of 300 cfs+450 cfs), and

therefore there is no more water to extract above 450 cfs. When the analysis was limited to the last 20 years (Assessment #2) the maximum amount of water extracted decreased in three of the four seasonal periods, by as much as 64% in the Summer Baseflow period (Figure 5B; Diehl, 2024) reflecting the recent lower flows. In the Early Runoff period, however, the maximum flow extracted increased slightly, from 1600 AF Day⁻¹ to 1700 AF Day⁻¹, suggestive of a shift in runoff patterns towards earlier snowmelt.

For a given volume of extracted water, the Early Runoff period experienced the least impact, and Summer Baseflow the greatest (Figure 5). This pattern held for both the full 99-year record (Assessment #1, Figure 5A) and the last 20 years (Assessment #2, Figure 5B). The slope of the volume-impact relation was indicative of the sensitivity of the resource to increasing water extraction (Figure 3). For both assessments, the slopes of the baseflow periods were an order of magnitude greater than those of the runoff periods (i.e., Early Runoff and Annual Flood). Additionally for the full hydrologic record, the slope of the Summer Baseflow period's relation (0.007) was twice that of the Winter Baseflow period (0.004), and the slope of the Annual Flood period's relation (0.0008) was four times that of the Early Runoff period (0.0002; Figure 5A). In recent years, the slope for the Early Runoff and Winter Baseflow remained unchanged, but the slope for the Summer Baseflow period doubled (0.013 for Assessment #2; Figure 5B), indicating that for a given volume of water extracted there was a greater resource impact when considering the past 20 years than when considering the full record. Between the two assessments, the shape of the Annual Flood volume-impact relation transitioned from a continuous relationship to a discontinuous one. Impacts associated with water extractions less than 125 AF Day⁻¹ had less of an impact on the resource when considering the past 20 years than when the full record was considered. Extractions greater than 125 AF Day⁻¹, however, had significantly larger impacts for Assessment #2. This threshold was driven by the Geomorphic Work metric, which when evaluated over a shorter time period, composed of drier years with less days that exceeded the 10,000 cfs threshold, was either minimally or substantially affected by the extraction scenarios.

Figures 6 and 7 show optimized volume-impact relations for the five hydrologic year types (i.e., Assessment #3), first grouped by hydrologic year type (Figure 6) and then grouped by seasonal period (Figure 7), to highlight how seasonal trends vary from one year to the next. In contrast to the relations in Figure 5, relations parsed by year type (as in Figures 6 and 7) are representative of the average volume and impact identified from the historical flow record.

For the Summer and Winter Baseflow periods, there was substantially more water extracted in wetter years than drier ones (Figures 6 and 7). The volume extracted for the Early Runoff and Annual Flood periods was less sensitive to the hydrologic year type, although there was a similar trend of greater water extracted in wetter years than drier ones. For all year types, impacts remained minimized for the Early Runoff period and were at a maximum for the Summer Baseflow period. Generally, the Winter Baseflow period had the second greatest impact followed by the Annual Flood, but in some year types (Wet and Average) the volume-impact relations overlap, blurring the distinction in impact between the two periods (Figures 6 and 7).

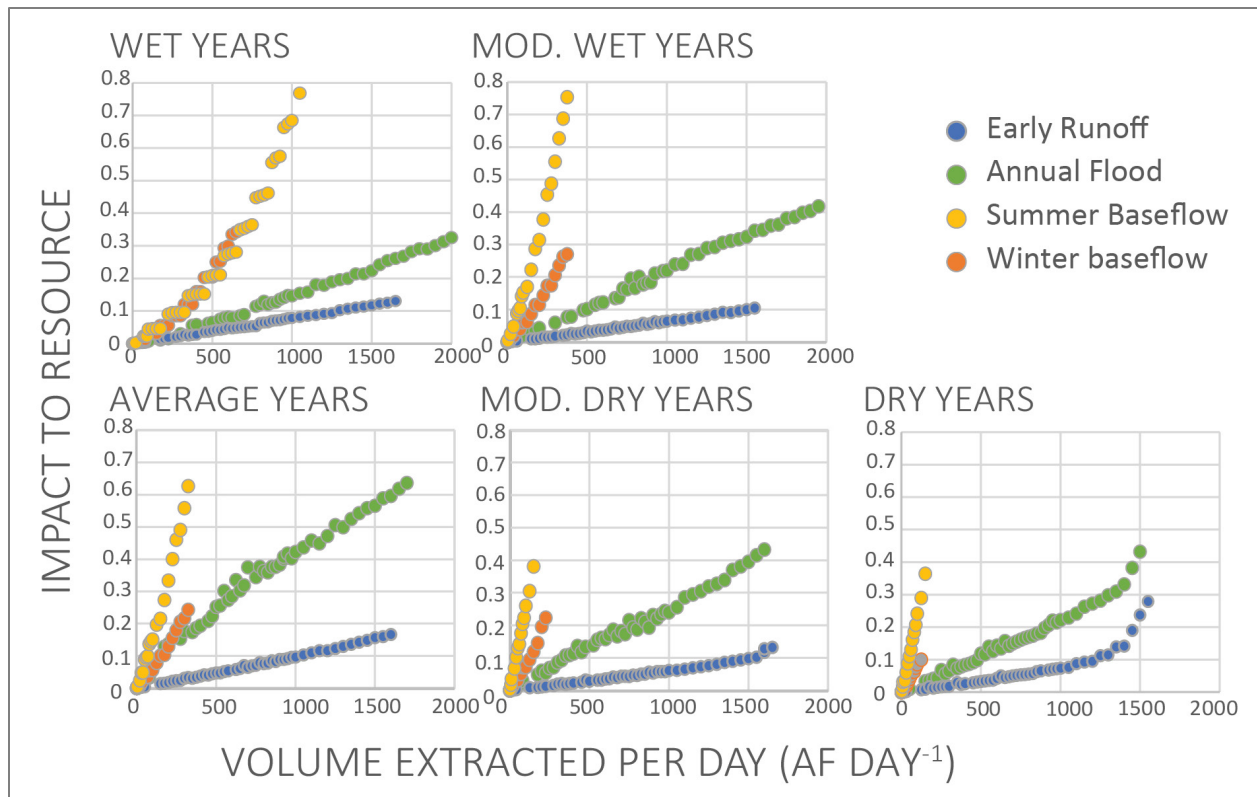


Figure 6. Optimized volume-impact relations for each hydrologic year type, broken down by seasonal period (Assessment #3). Relations represent average extracted volumes for historical record and average impact to resource. The range of data on the x axis is indicative of the maximum developed water considered given the 350 scenarios evaluated.

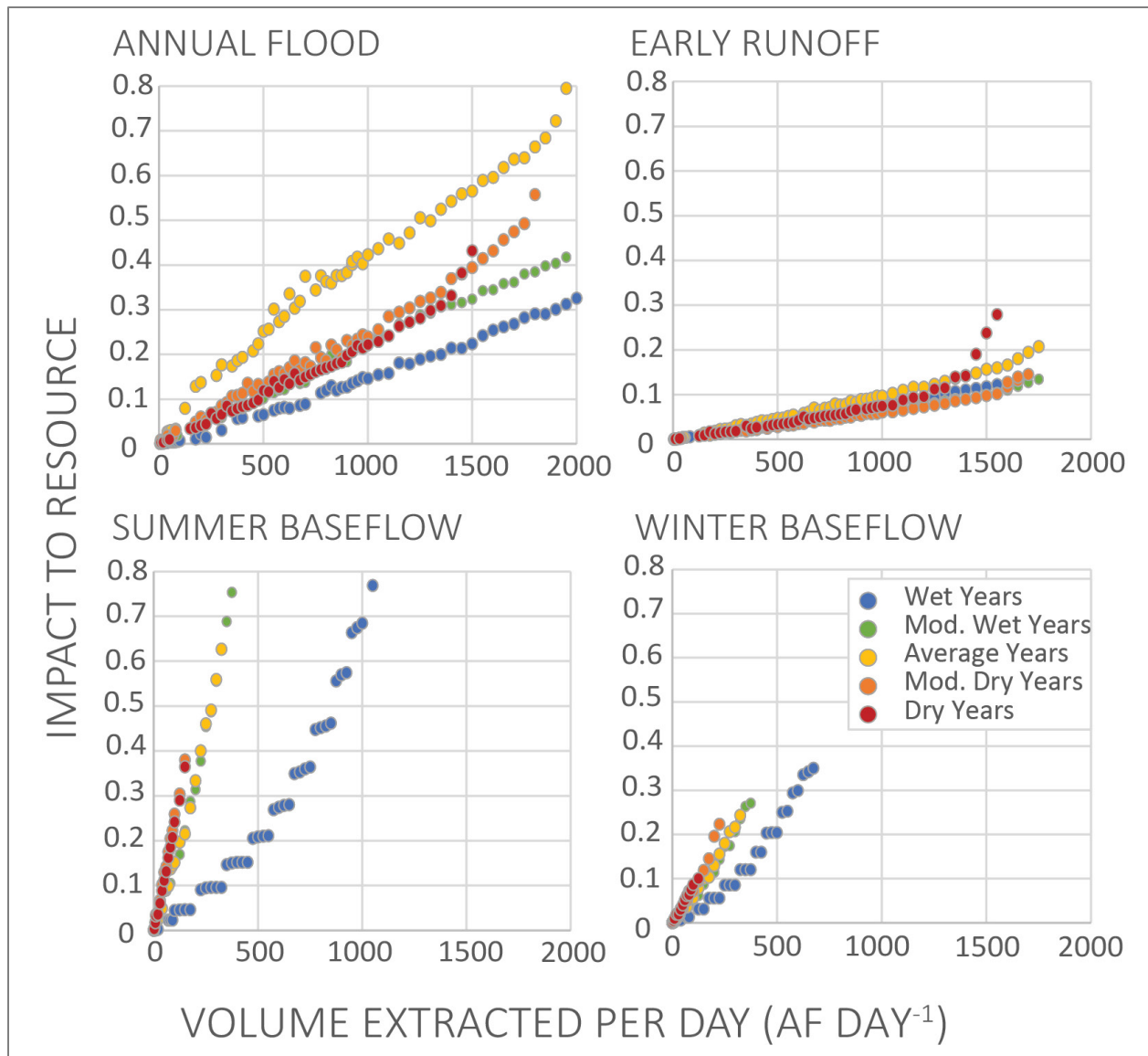


Figure 7. Optimized volume-impact relations for each seasonal period, broken down by hydrologic year type (Assessment #3). Relations represent average extracted volumes for historical record and average impact to resource. The range of data on the x axis is indicative of the maximum developed water given the 350 scenarios evaluated.

As in Assessments #1 and #2, slopes of the volume-impact relations for Assessment #3 were greatest during the two baseflow periods. In these baseflow periods, slope remained relatively constant between year types, except for the wettest years, when the sensitivity of the system decreased (Figure 7). The slope of the volume-impact relation for the Early Runoff period was consistently low, and the slope for the Annual Flood period was greatest during Average years, and least during Wet years.

Figure 8 shows the volume-impact relations broken down by period and resource metric to highlight the variable influence of the different resources on total impact within and between years. The resource metrics plotted in Figure 8 represent the average value calculated for a year type within each

period for each of the alternative scenarios identified by minimizing the total impact from extracting a given flow volume. As such, the sum of all resource metrics in a panel corresponds to the total resource impact presented in Figures 6 and 7.

In the Early Runoff period, changes to the Sediment Load were consistently greater than those to Fish Habitat Availability (Figure 8). From Wet to Dry years, the Sediment Load resource metric generally decreased (i.e., there were less changes to sediment loads in Dry years than Wet ones), while the Fish Habitat resource metric increased. As a result, in Dry years, the two metrics both contributed relatively equally to the total impact. In the Annual Flood, changes to Geomorphic Work were greater than to other resource metrics for all hydrologic year types, except Dry years, for which the Geomorphic Work resource metric dropped down to zero. The magnitude of the impact to Geomorphic Work was greatest for Average years and decreased for both wetter and drier years. Changes to the Sediment Load were second to Geomorphic Work in the Annual Flood period and the impact increased slightly for increasingly dry years; for example, extraction of 500 AF Day⁻¹ resulted in 5% change to the Sediment Load in Dry years and 3% in Wet years. Channel Width is impacted to the greatest degree during Dry years, significantly contributing to the total impact to the resource.

Although the changes to Fish Habitat Availability were relatively small during the runoff periods (Early Runoff and Annual Flood), Fish Habitat Availability became an important contributor to the total impact to the resource during the baseflow periods and was more sensitive to water extractions in the Winter compared to Summer Baseflow period (Figure 8). For increasingly dry conditions, there was a greater decrease in Fish Habitat Availability during the baseflow periods. For example, during the Winter Baseflow period, extraction of 125 AF Day⁻¹ resulted in a decrease in Fish Habitat Availability by 3% in Wet years and 9% in Dry years. Plant establishment and Water Temperature were both impacted to a larger degree during drier years than wetter ones. In the Summer Baseflow period, changes to the Water Temperature were the largest contributor to the total impact; Wet years represent an exception. In Wet years, significantly more water was extracted based on the set of alternative scenarios but the impact to Water Temperatures was reduced, notably for extracted volumes less than 500 AF Day⁻¹.

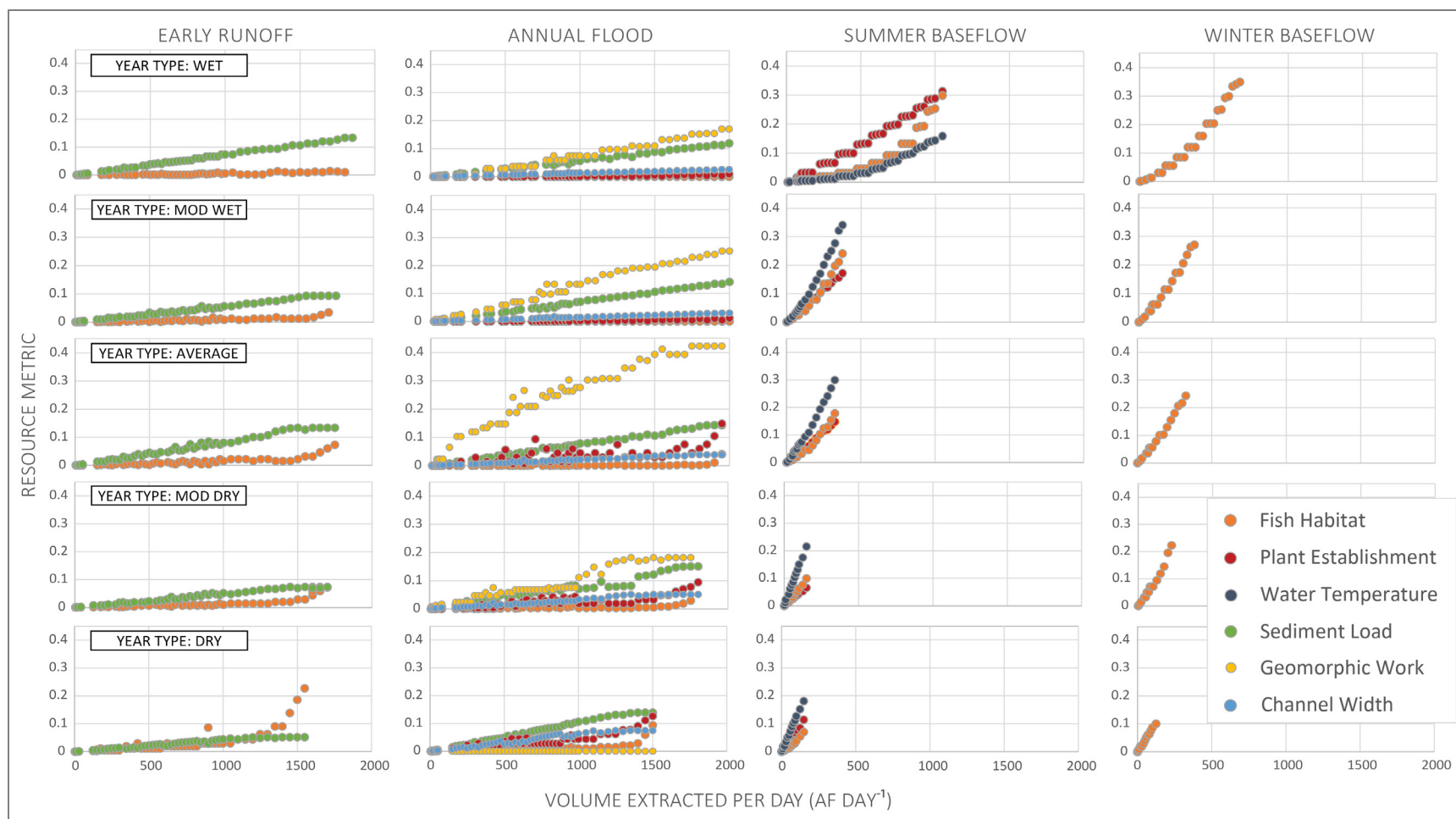


Figure 8. Optimized volume-impact relations by resource metric for each season and hydrologic year type. Relations represent mean extracted volumes for historical record and average partial impact to resource. The range of data on the x axis is indicative of the maximum developed water given the 350 scenarios evaluated.

Interpretation: Optimized Volume-Impact Relations

The historical analysis suggests that the natural resources of the Yampa River are expected to be impacted by the extraction of any amount of water. It is important to note that the total impacts and resource metrics shown in Figures 5–8 and reported in the Extraction Lookup Table (Diehl, 2024) are anticipated resource changes under alternative extraction scenarios relative to the historical record. As such, these changes would occur in addition to any other changes that may occur because of a changing climate, or because of altered runoff patterns from changing watershed conditions. For example, changes to Water Temperature will be further impacted by warming air temperatures, and if anticipated decreases to runoff (Salehabadi *et al.*, 2020) affect peak flows, then the predicted changes to channel width would be exacerbated by background changes not associated with flow extractions.

Within- and between-year variability in flows influences both the extracted water and the impact of extractions on the resource. Overall, we found that volumes extracted were higher and impacts of extraction were lower during runoff periods. In contrast, during baseflow periods, volumes extracted were lower and impacts were higher, notably during drier years.

If water must be extracted from the Yampa River, there are numerous advantages to doing so during the Early Runoff period. First, water extracted from the Early Runoff period consistently had less of an impact on the resource than a similar volume extracted during other periods (Figures 5–7). For the full historical flow record (Assessment #1), for example, extraction of 30 AF Day⁻¹ had a total impact of 0.005 during the Early Runoff period (Extraction Lookup Table, Assessment #1, Row 5, Diehl, 2024), 0.055 in the Annual Flood period (Row 64), jumping to 0.227 in the Summer Baseflow period (Row 136) and 0.098 in the Winter Baseflow period (Row 158). Additionally, the Early Runoff period is more reliable across year types than the other periods. In other words, there was less variability in the impact or volume between hydrologic year types than in the other periods (Figures 6 and 7). This consistency may be attributed to the shape of the hydrograph. Because flows for all hydrologic year types typically cross the MAF threshold during this period (Figure 1), the resource metric that relies on the hydrograph metric Flood Volume (i.e., Sediment Load) consistently dominated the total impact (Figure 8). In some of the driest years (i.e., 3 of the 10 Dry years in the historical record), the annual peak flow occurred during the Early Runoff period. This impact is not reflected in the relations presented in this report, as we do not consider Channel Width, which is associated with the Flood Peak metric, during the Early Runoff Period. However, in the future, as snowmelt runoff occurs earlier, it may be necessary to reconsider extractions during the Early Runoff period for impacts to Channel Width.

Extractions during the Summer Baseflow period, in contrast, would yield the least water and have the highest resource impact. In the historical analysis, extraction during summer baseflow consistently had the greatest impact on the resource relative to other periods (Figures 5–8). A steep slope to the volume-impact relation also indicates that the resource is highly sensitive to increasing extractions. This sensitivity remained high during most year types, decreasing with increasingly wetter conditions, notably for the wettest years.

Extractions during the Winter Baseflow and Annual Flood periods have moderate and variable impacts relative to the Summer Baseflow period, but there is significantly more water in the Annual Flood period (Figures 5–7). In the historical analysis, the Winter Baseflow period was increasingly sensitive to drier conditions. The response of the Annual Flood period was more complex. Average years had the greatest impact for a given volume of water extracted (Figure 7) because of the sensitivity during these years to the Flood Duration hydrograph metric, which informs the number of Geomorphically Effective Days (Figure 8). Historically, wetter years often remained above the effective discharge threshold and drier years often remained well below it (Figure 1). Average years, however, hovered around 10,000 cfs.

In the past 20 years runoff patterns on the Yampa River have shifted towards a greater prevalence of drier year types and less overall water (~7% less total volume in the historical hydrograph). The maximum volume of water extracted based on our extraction scenarios decreased significantly in the Summer Baseflow period but modestly increased during the Early Runoff period, indicative of earlier snowmelt and drier summers. Our analysis suggests that these shifts will not only reduce the water in the system but also increase the sensitivity of the resource to extractions. Notably, the Summer Baseflow period was twice as sensitive to increasing extractions in the past 20 years (Assessment #2, Figure 5B) than it was over the full hydrologic record (Assessment #1, Figure 5A). As the shift to lower, earlier runoff is expected to continue and potentially intensify, we expect that the resource will respond most similarly to the results for Assessment #2 and the drier year types.

Our analysis suggested that there are aspects of the resource that are most adversely affected by increasingly drier conditions. All the resource metrics in the Summer Baseflow period were particularly sensitive, notably Water Temperature. Between Wet and Dry years, the slope of the volume-impact relation for Water Temperature increased by an order of magnitude. And for the most recent 20 years, our analysis suggested that the impact to Water Temperature for the alternative hydrograph relative to the historical hydrograph was double for the same extraction when considering the full historical record. Channel width was also particularly sensitive to drier conditions. The slope of the Channel Width volume-impact relation tripled between Wet and Dry years and nearly doubled between Assessments #1 and #2.

Application: Integrating Analyses into Decision Making

The analyses presented in this document may be used as guidance for the NPS to evaluate how water development proposals will adversely affect NPS resources. Any amount of water withdrawal will have some impact on the natural resource of the Yampa River, and so the goal is to illustrate how to minimize those impacts to the extent possible. Below we provide three hypothetical examples of the type of decisions that may be made using the analyses in this document, and more specifically the volume-impact relations summarized in tabular format in the Extraction Lookup table (Diehl, 2024). The three use cases reference the volume-impact relations developed using both Assessment #1, the full hydrologic record, and Assessment #2, the most recent 20 years.

Use Case #1. The Park Service wants to define a limit on the impact to the resource from water development. For demonstration purposes, we define this limit as an approximate 1% change to the resource. In other words, the NPS wants to identify the extraction of water that is associated with less than a 1% change to any of the resource metrics compared to its historical condition. From the Extraction Lookup Table (Diehl, 2024), the user can identify the extracted volume of water (Columns 3 and 4) associated with a resource metric that is close to the 1% threshold (Columns 18 through 23). Extractions in the Early Runoff period would be limited to less than 60 AF Day⁻¹ or 2,820 AF over the full season (Assessment #1, Row 8, Diehl, 2024), which is associated with a 1.1% change to the Sediment Load and a 0.2% change to Fish Habitat Availability. It is important to note that based on the full historical record, in some years, there would not be a single day when this target daily extraction (e.g., 60 AF) would be met given the prescribed extraction parameters (2% of flows above 300 cfs not to exceed 75 cfs), and in half the years, it would only be met 53% of the days (see Columns 30 through 34). In the Annual Flood period, all extraction scenarios impacted an aspect of the resource by more than 1% relative to the historical condition for the full record (Assessment #1). If instead the NPS referenced the more recent 20 years, however, shifts in the volume-impact relations suggest that an extraction would be feasible in the Annual Flood period and limited to less than 100 AF Day⁻¹ or 7,500 AF over the full period (Row 69) before the threshold of acceptable impact was exceeded for the Sediment Load. For these prescribed extraction parameters (2% of flows above 300 cfs not to exceed 75 cfs), there may be years in which as much as 11,250 AF is extracted (column 9; based on the most recent 20 years), but there also may be years when only 3,825 AF is extracted. In the Summer Baseflow period, any extraction above 1 AF Day⁻¹ or 109 AF in the full period would impact Water Temperature above the 1% threshold, and in the Winter Baseflow period, extractions above 4 AF Day⁻¹, or 537 AF in the full period, would impact Fish Habitat Availability above the 1% threshold. The thresholds in this example are for individual resource metrics, and the cumulative impact for any given scenario is greater for the Annual Flood, Early Runoff, and Summer Baseflow periods because multiple aspects of the resource are affected by flows in these periods.

Use Case #2. An extraction of 10,000 AF is proposed to occur every year to an off-channel reservoir, but because the water can be stored, timing of extraction is flexible. When should the extraction occur to minimize impact to the resource? What are the optimal extraction parameters?

From the tools provided in this document, and summarized in Table 6, it is apparent that extractions focused during the Early Runoff period would cause the least impact to the resource. In the Extraction Lookup Table, Assessment #1 (Diehl, 2024), under Early Runoff (Rows 1 to 59), the user can look at Column 4 to find the total volume of flow that is extracted 75% of the time (25th percentile), and an associated set of prescription parameters that minimize the impact to the resource (Columns 1 and 2). Based on the full historical record (Assessment #1), 10,000 AF is optimized when 10% of the streamflows above 300 cfs are extracted, not to exceed 200 cfs on any given day (Row 17). This is associated with a removal rate of 250 AF Day⁻¹ (Column 3), and a total impact of 0.050 (Column 5). For comparison, for the full record, 10,000 AF is associated with a total impact to the resource of 0.192 in the Annual Flood, 0.784 in the Summer Baseflow, and 0.281 in the Winter Baseflow (Table 6).

The analysis on the more recent 20 years (Assessment #2) suggests that an extraction of 10,000 AF would, like Assessment #1, have the least impact on the resource in the Early Runoff period. The impact to the resource and extraction parameters needed to meet that extraction target during the Early Runoff period remain relatively consistent in Assessment #2, 0.046 (Row 17). In contrast, an extraction of 10,000 AF resulted in greater impacts to the resource relative to the full historical record (Assessment #1) for the Annual Flood period, which was more than four times greater based on the most recent 20 years (0.989 vs 0.192) and the Winter Baseflow period, which had a more modest increase (0.308 vs 0.281). For the Summer Baseflow period, 10,000 AF could not be extracted based on the more recent 20 years.

It is important to note that the extraction parameters necessary to meet a 10,000 AF extraction target 75% of the time in the Early Runoff period will result in as much as 18,800 AF extracted in some years (Assessment #1; Column 9), or as little as 6,580 AF in others (Assessment #1; Column 6). Additionally, the impact will not be borne equally across years, and may be as high as 0.058. Most of the impact on the resource is associated with a decrease to the Sediment Load (3.7% change; Column 21), and to a lesser degree to Fish Habitat Availability (1.2%; Column 18).

Use Case #3. An extraction of 40 AF Day⁻¹ (20.2 cfs) each day throughout the year (14,600 AF annual total) is proposed. What is the impact to the resource? What are the optimal extraction parameters to minimize the impact? From the optimized volume-impact relations summarized in the Extraction Lookup Table (Diehl, 2024), the user looks under Column 3 to find extraction parameters associated with approximately 40 AF Day⁻¹ for each of the four periods (Assessment #1: Rows 6, 65, 137, and 159). These extraction parameters are summarized in Table 6. Based on Assessment #1, there is a large range of impacts associated with targeting a consistent extraction rate across periods, from 0.007 during the Early Runoff period to 0.262 during Summer Baseflow (Column 5 in Extraction Lookup Table; Table 7).

Table 6. Summary of extraction parameters, extracted volumes, and associated impacts for a scenario in which 10,000 AF is extracted during a single period.

Assessment	Period	Flow Extraction Parameters		95th percentile Impact	Range of Impacts	Range of extraction volumes (AF)
		% Extraction	Maximum Extraction (cfs)			
#1 Full Record	Early Runoff	10%	200	0.050	0.000 – 0.058	6580 – 18800
	Annual Flood	2%	100	0.192	0.004 – 1.030	3750 – 15000
	Summer Baseflow	100%	300	0.784	0.000 – 0.962	0 – 64310
	Winter Baseflow	70%	350	0.281	0.001 – 0.296	134 – 76523
#2 Recent 20 years	Early Runoff	10%	150	0.046	–	8930 – 14100
	Annual Flood	2%	150	0.989	–	3900 – 21750
	Summer Baseflow	N/A	N/A	N/A	N/A	N/A
	Winter Baseflow	80%	800	0.308	–	134 – 85920

Table 7. Summary of extraction parameters, extracted volumes, and associated impacts for a target extraction of 40 AF Day⁻¹ each day throughout the year.

Assessment	Period	Flow Extraction Parameters		95th percentile Impact	Range of Impacts	Range of extraction volumes (AF)
		% Extraction	Maximum Extraction (cfs)			
#1 Full Record	Early Runoff	5%	25	0.010	29 – 50	1363 – 2950
	Annual Flood	2%	25	0.060	26 – 50	1950 – 3750
	Summer Baseflow	90%	100	0.360	0 – 225	0 – 21800
	Winter Baseflow	40%	250	0.135	0.6 – 390	81 – 52358
#2 Recent 20 years	Early Runoff	5%	25	0.012	41 – 50	1927 – 2350
	Annual Flood	5%	25	0.017	30 – 50	2250 – 3750
	Summer Baseflow	N/A	N/A	N/A	N/A	N/A
	Winter Baseflow	50%	450	0.175	0.7 – 350	94 – 46988

In recent years, the impact associated with a consistent extraction of 40 AF Day⁻¹ more than doubled for the Summer Baseflow period (0.262 to 0.553) and increased more modestly for the Early Runoff and Winter Baseflow periods, while the impact to the Annual Flood decreased (Extraction Lookup Table, Assessment #2, Diehl, 2024). In drier years, which have occurred more frequently in recent years, the Geomorphic Work resource metric is impacted to a lesser degree than other year types (Figure 8), because in Dry years the annual flood does not often cross the 10,000 cfs threshold.

The prescription parameters identified in Table 6 were chosen to assure that based on the historical record, 40 AF could have been extracted daily for 75% of the years evaluated. Because of the large variability in flows, however, it is important to note that for some days the target extraction of 40 AF would not be met. In Columns 30–34, the proportion of days in a given year (within a period) for which the target extraction is met are listed. In some years, 40 AF Day⁻¹ could not be extracted for any days without breaking the rule preventing flow diversions when daily flow is below 300 cfs. In most years, more than half the days will meet the 40 AF Day⁻¹ target.

Conclusions and Additional Considerations

The flow prescription (extraction) concept developed in this document relies on a reverse quantification approach to preserve the daily, seasonal, and annual flow variability necessary to maintain the riverine and riparian resource along the Yampa River. From a historical analysis of streamflows that have occurred during the past century, we identified a range of water volumes extracted and the expected range of impacts on the resource for a variety of flow extraction scenarios. The results of the historical analysis highlight that (1) extraction of any water would have an adverse impact on the resource and that (2) extraction of water from some parts of the hydrograph would have less impact on the resource than others. Impacts of flow diversions were generally lowest during the Early Runoff Period and highest during the Summer Baseflow period. This result suggests moving as many current and future diversions as possible to the Early Runoff period. A limitation of this approach is that it could require construction of additional reservoirs, with associated economic and environmental costs, to hold water diverted during Early Runoff for use later in the year.

Increasing temperatures associated with global change are causing decreased runoff volume and earlier runoff timing (Stewart *et al.*, 2005), trends that are likely to accelerate into the future (Salehabadi *et al.*, 2020). This trend was apparent in the comparison of results for Assessment #1 (full hydrologic record) and Assessment #2 (recent 20 years). In three of the four periods analyzed less water was extracted in the recent 20 years for the range of extraction scenarios than in the full historical record. By comparing the volume-impact relations between the two assessments, our results allow for an evaluation of how we might anticipate the resource will respond to extractions in the future. The greater frequency of drier years in recent decades, which is likely to persist or worsen, suggests that the Yampa River's natural resources are growing increasingly sensitive to water diversions. As a result, it will become more challenging to identify places in the hydrograph where development needs may be met without impacting the resource beyond an allowable limit, as determined by the NPS or other stakeholders.

While our analyses provide robust data to evaluate the impacts associated with extractions, there are limitations to our approach. The evaluation of changes to the resource, summarized by the resource metrics and impact values, are based on those aspects of the resource where we can draw a direct linkage between a single functional flow component and a single characteristic of the resource. But the natural resource is defined by complex interactions and feedbacks among the hydrograph, fluvial processes, and ecological response, and there are aspects of the resource where the direct linkage is not as apparent, or the scientific understanding of the linkage is limited. This is particularly true for native fish dynamics, which respond to reproductive signals in the hydrograph, non-native fish predation, and the condition of the geomorphic template. The resource metrics in this study for native fish directly capture limitations in habitat availability and water temperatures that may stress adults with water extraction, but likely miss some of the non-linear effects of flow changes on recruitment and non-native predation. For example, extraction from the Annual Flood may influence the timing of spawning cues for non-native fish and diminish the recruitment constraints that the high flows provide. Further, extractions from the Annual Flood will lead to a non-linear response in the physical

template of critical fish habitat. Manners et al. (2014) documented a 6% decrease in channel width on the Yampa River in DINO over a 50-year period, despite no significant changes to peak flow magnitude. Instead, they attributed the narrowing to shifts in the sequencing of hydrologic year types, more specifically to an increase in occurrence of multiple-year droughts that promoted establishment of riparian vegetation lower in the channel, enhancing deposition rates that resulted in floodplain construction, and limited the efficacy of floodplain stripping events. Thus, predictions of channel narrowing may be an underestimation of actual changes because of concurrent increases in geomorphically-consequential plant establishment in the channel, decreases to the sediment load, and decreases in geomorphically-effective flows. Finally, our analyses do not consider that water extracted in one period may also influence flow conditions in another. Extracting water from the Early Runoff period has the potential, for example, to decrease soil moisture along the river corridor and affect streamflow levels in the Annual Flood period.

There are additional limitations in how our approach accounts for ongoing and future shifts in runoff patterns. The historical analysis and the resulting flow extraction tools examine each year in isolation and do not account for the sequencing of years. Impacts of extraction from Dry years, for example, were quantified in isolation, but extraction from a Dry year that follows two other Dry years is likely to have greater impacts. We attempted to account for this in the Plant Establishment resource metric, but there are other flow sequence effects not addressed by our model. Shifting runoff patterns are also influencing the clustering of wetter and drier years in time, which can have a significant impact on the resource (Manners *et al.*, 2014). Unprecedented dry years and extended sequences of dry years in a row would intensify the resource impacts associated with low flows, including high water temperature. In the historical record, flow peaks tended to be earlier in the Dry and Moderately Dry types than in the wetter types (Figure 1). In all but three years of the 99-year historic record, the peak annual discharge occurred during the Annual Flood period (May 1–July 15). All three exceptions (1946, 1989, 2012) were Dry or Moderately Dry years in which the peak annual discharge occurred during the Early Runoff period. In such years, flow prescriptions targeting the Early Runoff period for flow extraction will unintentionally reduce the annual peak. Evidence of a larger proportion of runoff occurring earlier in the year in recent decades is likely to continue. In the future, as climate change alters the timing of annual hydrologic events and other characteristics (e.g., flashier runoff), definitions used in our model (i.e., seasonal period thresholds) may need to be adjusted.

Our analysis does not distinguish between flow originating in the Yampa River above Maybell (the source of most of the water at Deerlodge Park) and flow originating in the Little Snake River (the source of most of the sediment; Topping et al., 2018). This simplification resulted from our focus on conditions in DINO and the need to minimize complexity. As a result, we do not address effects of future changes in the ratio of flow from these two sources, or of ongoing decadal-scale decreases in sand supply from the Little Snake River (Kemper *et al.*, 2022). Changes to sediment supplies or transport capacity influence sediment loads along the Yampa River in DINO in complex non-linear ways over multiple decades (Topping *et al.*, 2018), altering vegetation community composition (Kemper *et al.*, 2022), and channel geometry (Leonard and Schmidt, 2019). Interpretations of impacts in our analyses relied on simple rating curves developed under assumptions of stationarity.

The absence of large dams on the Yampa River maintains large flow variability and high sediment loads that result in the wide, shifting, and complex channel, which favors native fish and vegetation. Ironically, the lack of a large dam also makes the Yampa more susceptible to episodes of extreme low flow and high-water temperature in summer. Along regulated streams like the Green River downstream of Flaming Gorge Dam or the Colorado River downstream of Lake Powell, release of water from deep in the reservoir keeps water temperature artificially low, and water can be released from the reservoir to prevent extreme low flows during hot conditions. Along the Yampa River, diversions have already greatly decreased summer baseflows (Table 1) and there are limited options for increasing flow or decreasing water temperature during low-flow emergencies. This presents a risk to native fish and riparian trees that will worsen as climate change leads to increased temperature and decreased flow. Managers are already working to prevent episodes of zero flow on the Yampa River in the fall. Most days of extremely high-water temperatures (above 30° C) occur in July because of higher sun angles and longer days. In future years, high July water temperatures could present a serious risk for native fish in dry years and with warmer air temperatures. The Water Temperature resource metric is designed to address this issue but focuses only on the impact of decreasing discharge and does not examine the effects of air temperature month by month. Because water temperatures are highly sensitive to air temperature (Poole and Berman, 2001), the impacts of water extraction are likely to be amplified in the future, beyond what our resource metric may suggest.

Our assessment of the relationship between hydrograph changes and resource impacts is based on the best science that may be integrated into a flow extraction assessment. Ongoing research will refine existing relations among Yampa River streamflow, channel geometry, and habitat for riparian vegetation or endangered fish, or will develop new relations, for example, relating flows to newly arrived invasive species. As the science evolves, and runoff patterns change, it may be necessary to adjust hydrograph or resource metrics or the definition of seasonal periods. Continued monitoring of the resource is essential to assess effects of flow alteration and refine models of resource impacts.

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Appendix A: Historical Analysis of Flood Peaks and Annual Flow Volume

Figure 9 shows the annual peak flood magnitude of the Yampa River from 1922–2018.

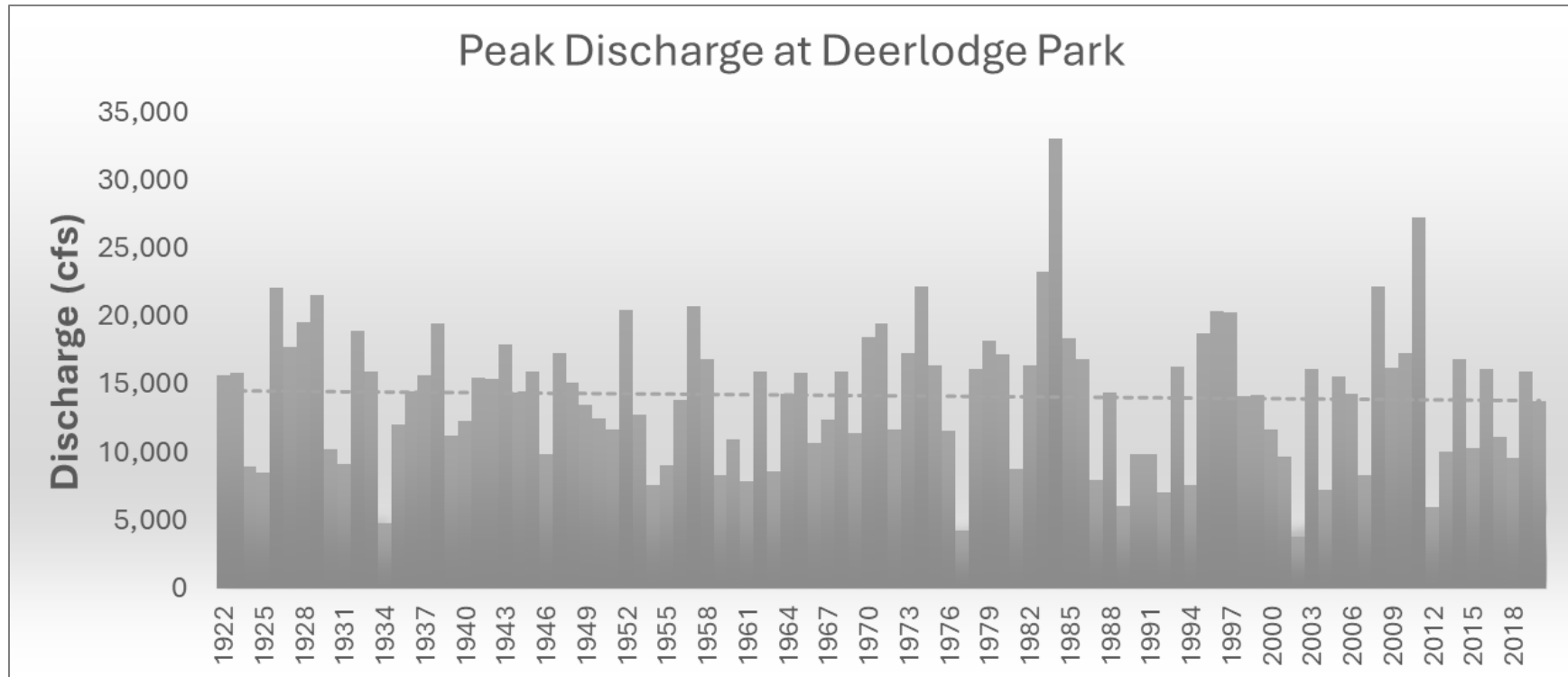


Figure 9. Historical annual peak flood magnitude of the Yampa River for the 99-year record, measured at Deerlodge Park, CO, for 1982–2020 and reconstructed from the records for the Yampa River at Maybell, CO and the Little Snake River at Lily, CO from 1922–1981. There is no significant trend (dashed line; $p=0.70$) in annual flood peak over the historical record.

Appendix B: Functional Flow and Other Components

Below we provide greater details on the importance of the four main functional flow components that define the annual hydrograph and their importance for ecological and physical processes that support native fishes, riparian vegetation, and the geomorphology of the Yampa River. We also list three functional flow components that describe between-year variability in the annual hydrograph (#5–#7 below) and an additional four factors (#8–#11) that are particularly responsive to flows, describing their importance to the resource and their relationship to functional flow components. Greater details on many of these items may be found in individual subject matter expert reports (Bestgen, 2015; Scott and Friedman, 2018)

1. Winter Baseflow

- a. Flows of 200–300 cfs provide relatively diverse habitat for Colorado pikeminnow (*Ptychocheilus lucius* Girard) upstream of the Little Snake confluence in winter (Wick and Hawkins, 1989).
- b. Winter is the dormant season for plants, limiting the effects of flow variation on plant survival; however, flow variation in winter can lead to physical removal of encroaching vegetation, and these effects may be magnified by ice (Johnson, 2000; Lind *et al.*, 2014).
- c. Winter fluctuations that break ice cover can be disruptive to native fish (Bestgen, 2015).

2. Early Runoff

- a. Usually includes the rising limb of the snowmelt hydrograph, and in low-flow years, has the potential to include the peak (this occurred in three of the 99 years of the flow record for Deerlodge Park).
- b. Least damaging time for diversion effects on fish and vegetation, because water is relatively abundant, temperatures high enough to injure fish are unlikely and vegetation is dormant.
- c. Fish are eating more in response to ice-off and rising temperatures and are developing gametes (Bestgen, 2015).
- d. Relatively little concern about disruption of reproductive cues if altered (Bestgen, 2015).
- e. Extreme withdrawals at this time could warm water, accelerating gamete development and leading to reproductive readiness too early; this has occurred below McPhee Reservoir on the Dolores River (Bestgen *et al.*, 2011).
- f. This is the time of highest sediment loads necessary to form secondary channel and backwater habitats, but it is unknown to what extent reducing early-season flows would reduce sediment delivery on an annual basis as opposed to just delaying it.

3. Annual Flood

a. Magnitude

- i. High variability in flow within years removes vegetation through erosion, extended inundation and desiccation, creating the broad, open surfaces in and near the channel that are characteristic of lightly regulated rivers in western North America (Scott and Friedman, 2018).
- ii. Flows with recurrence interval of >10 years (20,500 cfs at Deerlodge Park) are necessary for general mobilization of gravel and cobble in Yampa Canyon, removal of established riparian vegetation from secondary channels and remobilization of tributary fans (Harvey *et al.*, 1993; O'Brien, 1984).
- iii. Common floods between 1.25- and 10-year recurrence interval (9,840–20,500 cfs at Deerlodge Park) transport 47% of annual sediment flux (more important than extreme floods for volume of sediment transport) (Elliott and Anders, 2005).
- iv. Common floods can prevent establishment of vegetation in secondary channels (Manners, 2013).
- v. Flows above 10,000 cfs sort, clean, and redistribute gravel and cobble near spawning sites (Mussetter *et al.*, 2001).
- vi. Form and flush spawning habitat and invertebrate habitat (Bestgen, 2015).
- vii. Form secondary channels and backwaters for nursery habitat (Bestgen, 2015).
- viii. Signal for fish to begin reproductive activities (Bestgen, 2015).
- ix. Entrain nutrients from floodplain (Welcomme, 1995).
- x. Form and fill warm low-velocity ponds to improve fish body condition (Muth *et al.*, 2000).
- xi. Pikeminnow larval abundance is positively correlated with peak magnitude, and peak flows below 10,000 cfs at Deerlodge Park are associated with low pikeminnow larval abundance (Bestgen, 2015).
- xii. Promote these benefits downstream along Green River (Bestgen, 2015).
- xiii. Most non-native species decline in years of high peak flows, but northern pike (*Esox lucius* L.) reproduction may benefit from high flows (Bestgen, 2015).
- xiv. Reduction in peak flows reduces shear stress on banks, reducing the size of boulders that can be moved or locations of the floodplain where erosion can

be initiated. Where banks erode by undercutting, peak flow magnitude may be less important than duration (Grams *et al.*, 2020).

- xv. Reduced peaks (or increased base flows) promote proliferation of bank vegetation promoting sediment deposition leading to channel narrowing and simplification (Scott and Friedman, 2018).
- xvi. Reduced peaks (or increased base flows) also increase area of plant species associated with extremely high and low inundation durations relative to species associated with moderate inundation duration (Auble *et al.*, 1994).
- xvii. Reduced peaks (or increased base flows) decrease occurrence of species tolerant of fluvial disturbance, while increasing occurrence of species tolerant of extended inundation (Scott and Friedman, 2018).
- xviii. Decrease in spring high-flow peaks and duration decrease area and duration of floodplain inundation, which decreases floodplain recharge favoring drought tolerant tamarisk (*Tamarix* spp.) over more drought-sensitive native plants (Scott and Friedman, 2018).

b. Timing

- i. Along the Yampa River, Fremont cottonwood (*Populus fremontii* S. Watson) seed dispersal occurs over a 4–6 week period coinciding with declining river stage following the annual peak. At Deerlodge Park, cottonwood seed dispersal occurred from early June to mid-July in 1994 and from late June to late July in 1995. In 1995, tamarisk seed dispersal at Deerlodge Park began later than that of cottonwood, in early to mid-July, and continued until mid-September (Cooper *et al.*, 1999). Recent warming has advanced tamarisk seed release so that it now begins around the same time as cottonwood (Luke Gommerman, NPS, written personal communication, 2023).
- ii. Peak flows late in the growing season promote establishment of tamarisk seedlings relative to those of cottonwood and sandbar willow *Salix exigua* Nutt. (Cooper *et al.*, 2003).

c. Descending Limb of Annual Flood

- i. Flows from 500–4000 cfs in descending limb cut through loose cobble and create fresh spawning substrate with abundant interstitial spaces for eggs of pikeminnow and other native fishes (Bestgen, 2015).
- ii. Most native fish reproduce during descending limb (Bestgen, 2015).
- iii. If too steep, may affect cues for spawning movements or reproduction, may aerially expose pikeminnow eggs, or may not transport larvae far enough downstream.

- iv. Reduced flows could warm water and shorten reproductive season causing more spatial and temporal overlap of spawning seasons of different species resulting in hybridization among native suckers (razorback (*Xyrauchen texanus* Abbott.), flannelmouth (*Catostomus latipinnis* Baird & Girard), and bluehead (*Catostomus discobolus* Cope.) and with invasive white suckers (*Catostomus commersoni* Lacepede) (Bestgen, 2015).
- v. Native fish are main channel spawners dependent upon descending limb flows to flush spawning gravel and provide sufficient depth during spawning and to maintain interstitial flow through gravel for embryo and larval development (Bestgen, 2015).
- vi. Reduced flows would increase temperatures allowing earlier spawning of smallmouth bass (*Micropterus dolomieu* Lacepede) which begins when T exceeds 16°C in the descending limb (Hill and Bestgen, 2014).
- vii. Descending limb for Yampa usually coincides with prescribed Green River peak which is delayed until razorback sucker larvae are present on the Green (Muth *et al.*, 2000).
- viii. Rapid flow decline could promote bank collapse (maintaining channel width) because high weight and pore-water pressure in the wet bank would not be counteracted by pressure of standing water next to the bank (Simon and Collison, 2002).
- ix. Cottonwood seedlings may be killed by stage declines over 2.5 cm/day. This guideline depends upon age of seedlings, sediment particle size, and effect of recent rain on soil water availability (Scott and Friedman, 2018).

4. Summer Baseflow

- a. Most altered aspect of Yampa flow regime; declined 37% 1922–2013 (Bestgen, 2015).
- b. Late summer base flows are lowest naturally and because of agricultural demand.
- c. Maintain habitat depth and area and food availability especially in riffles, which are naturally shallow. Maintain depth for adult fish movement, including post-spawning pikeminnow. Maintain depth in backwaters for early life stages.
- d. Higher summer base flows keep water cool to reduce growth of invasive smallmouth bass (Bestgen, 2015).
- e. Most non-native fish species decline in years of high base flows (Bestgen, 2015).
- f. In Yampa above Little Snake 93 cfs is minimum flow to satisfy foraging depth in riffles for pikeminnow (Modde *et al.*, 1999). Anderson and Stewart (2007) recommend minimum base flow of 200–300 cfs at Maybell, and Bestgen (2015) concurs for all but driest years. Increasing summer base flow to 300 cfs may

increase biomass of native suckers, and flow-habitat-biomass relationships are optimized at base flows of 650 cfs (Anderson and Stewart, 2005).

- g. Decrease in summer base flows could kill drought sensitive native forest species like cottonwood (Williams *et al.*, 2022) and could favor drought tolerant plants like tamarisk over more drought-sensitive native species (Scott and Friedman, 2018).

5. Within-Year Flow Fluctuations (in all periods)

- a. Multiple peaks in Early Runoff or Annual Flood periods could promote bank retreat by filling the bank with moisture, removing supporting pressure of high stage to allow bank collapse and then repeating (Simon and Collison, 2002).
- b. Flow fluctuations disrupt fish, especially early stages with limited mobility.
- c. Summer peaks of short-duration (up to a few days) during the base-flow period, (around July 1), can sweep eggs and weak-swimming larvae of invasive smallmouth bass from nests, and associated increased turbidity reduces feeding success of the larvae. In contrast, native fish are relatively tolerant of flow fluctuations and turbidity (Bestgen, 2015).
- d. Flow fluctuations in winter can lead to physical removal of encroaching vegetation, and these effects may be magnified by ice (Johnson, 2000; Lind *et al.*, 2014). On the other hand, winter fluctuations that break ice cover can be disruptive to native fish (Bestgen, 2015).
- e. Rapid declines in the descending limb of the hydrograph kill riparian woody seedlings by desiccation. Fluctuations in the descending limb can kill seedlings by desiccation and inundation. Thus, rapid declines and fluctuations would be counterproductive following early-season peaks prescribed to promote cottonwood but would be consistent with the goal of preventing tamarisk establishment following a late-season peak (Scott and Friedman, 2018).

6. Between-Year Flow Variability

- a. Large peaks in some years are necessary to maintain channel width and complexity.
- b. In low-flow years water is warmer and native fish reproduce earlier (Bestgen, 2015).
- c. Two or more years in a row with similar peak and base flows promote establishment of woody vegetation. Subsequent sediment deposition around this vegetation, especially if the vegetation is tamarisk, results in channel narrowing and simplification (Scott and Friedman, 2018).
- d. The tendency of regulated flows to keep returning to a small number of fixed discharge values (such as power plant capacity or a fixed minimum flow) can cause unnaturally sharp banding of geomorphic surfaces, topography and vegetation lines that are not necessarily erased by large flood peaks (Scott and Friedman, 2018).

7. Annual Flow Volume

- a. Yampa River Programmatic Biological Opinion (U.S. Fish and Wildlife Service, 2005) stated that existing depletions (up to 167,854 AF) plus new depletions (up to 53,532 AF) would not jeopardize the continued existence of endangered fishes as long as natural annual flow patterns (including spring peak) are maintained and base flows are augmented.

8. Sediment

- a. Sediment transport is likely highest during ascending limb of spring peak when sediment is available in channel margins and during summer thunderstorms carrying sediment from small tributaries.
- b. Changes in sediment load relative to transport capacity may promote channel change especially in alluvial settings, but these changes are difficult to predict. For example, decreases in sediment input from the Little Snake River Basin (Kemper *et al.*, 2022; Topping *et al.*, 2018) may be promoting erosion and channel widening in Deerlodge Park through undermining of decades–centuries old floodplain surfaces leading to bank collapse. On the other hand, decreased sediment transport is also resulting in decreased rate of bar formation, which could eventually decrease channel width, complexity, and migration rate (Kemper *et al.*, 2022). Diversion of water from the upper Yampa Basin would tend to cause sediment surplus and decreased physical disturbance at Deerlodge Park, which could lead to channel narrowing.
- c. Whereas flood regime and coarse sediment mobilization control channel morphology in Yampa Canyon, sediment mass balance may control channel change at Deerlodge Park.
- d. High turbidity disadvantages sight-feeding invasive predators including smallmouth bass and northern pike but may also cause some stress to early stages of native fish; for example, high turbidity may cause pikeminnow larvae to emerge early from spawning gravel (Bestgen, 2015).
- e. Yampa River sediment is important for formation of backwater habitat for young pikeminnow in Yampa and downstream in the Green River (Bestgen, 2015).

9. Temperature

- a. Native fish tolerate warm temperatures, but warm temperatures stimulate growth of smallmouth bass, which can grow 2–3 times as fast as natives, and channel catfish (*Ictalurus punctatus* Rafinesque) leading to predation. Increase in summer temperature from reduced flows or global change could favor smallmouth bass and channel catfish (Bestgen, 2015).
- b. Extremely cold hypolimnetic releases from dams could damage native fish and smallmouth bass (Bestgen, 2015).

- c. Warm temperatures are apparently limiting downstream migration of invasive white sucker (Bestgen, 2015).
- 10. Salinity
 - a. Increased irrigation return flows from soils derived from marine shales combined with increased diversion of low-salinity flows from high in the basin could increase river water salinity. Increases in salinity of water or soil would promote tamarisk over the native woody species (Scott and Friedman, 2018). Even if water salinity does not increase, floodplain soil salinity can be increased by decreasing the flushing caused by overbank flooding.
- 11. Connectivity
 - a. Pikeminnow and razorback sucker need to migrate along the Yampa to find habitat for all life phases. For example, some pikeminnow spawn in the lower Yampa River but spend the rest of their life cycle as much as 360 km or more downstream (Bestgen, 2015). River-spanning structures could interfere with this migration.
 - b. Sediment from Muddy Creek, Sand Creek, Powder Wash and Sand Wash in the Little Snake River Basin is important to habitat downstream in the Yampa and Green rivers (Kemper *et al.*, 2022).

Appendix C: Procedural Summary

Figure 10 describes the methodology used to define volume-impact relations for Assessments #1, #2, and #3.

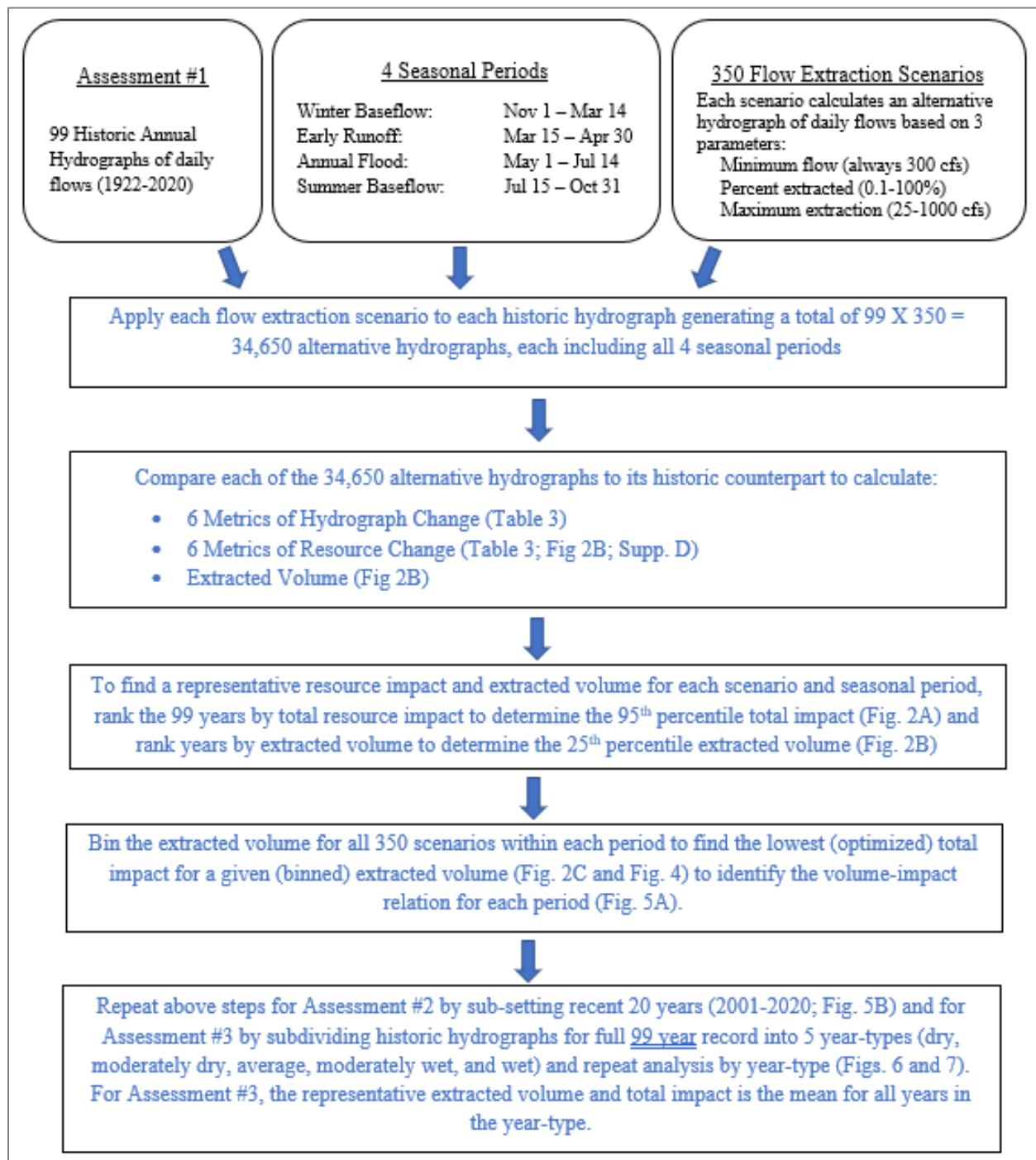


Figure 10. Schematic illustration of the process and steps taken to develop optimized volume-impact relations by resource metric for each season and hydrologic year type for each of three Assessments.

Appendix D: Additional Information on Hydrograph and Resource Metrics

Bed Coverage Hydrograph Metric and Fish Habitat Availability Resource Metric. We assumed that there was a direct relationship between the coverage of the channel bed, measured as the proportion of flows below 600 cfs altered for a given scenario, and the available fish habitat. As such, the Fish Habitat Availability resource metric was directly related to the Bed Coverage hydrograph metric (Figure 11).

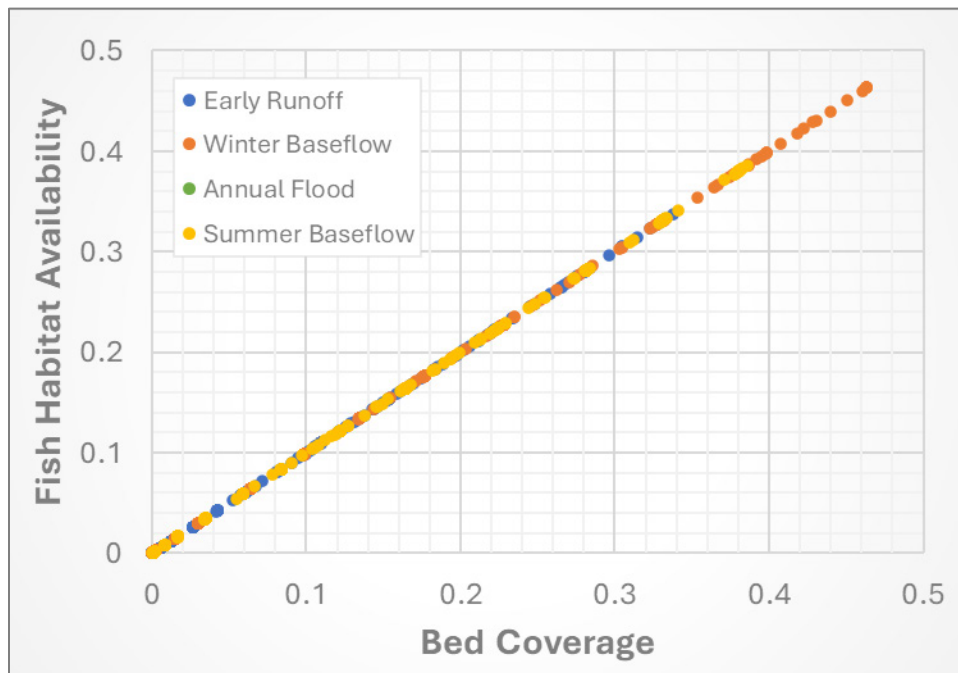


Figure 11. Relationship between the Bed Coverage hydrograph metric and Fish Habitat Availability resource metric, which was applied to all four seasonal periods.

The Bed Coverage metric was identified at the USGS Deerlodge Park stream gage using an inflection point in the relationship between discharge and channel width derived from field measurements (see Figure 12).

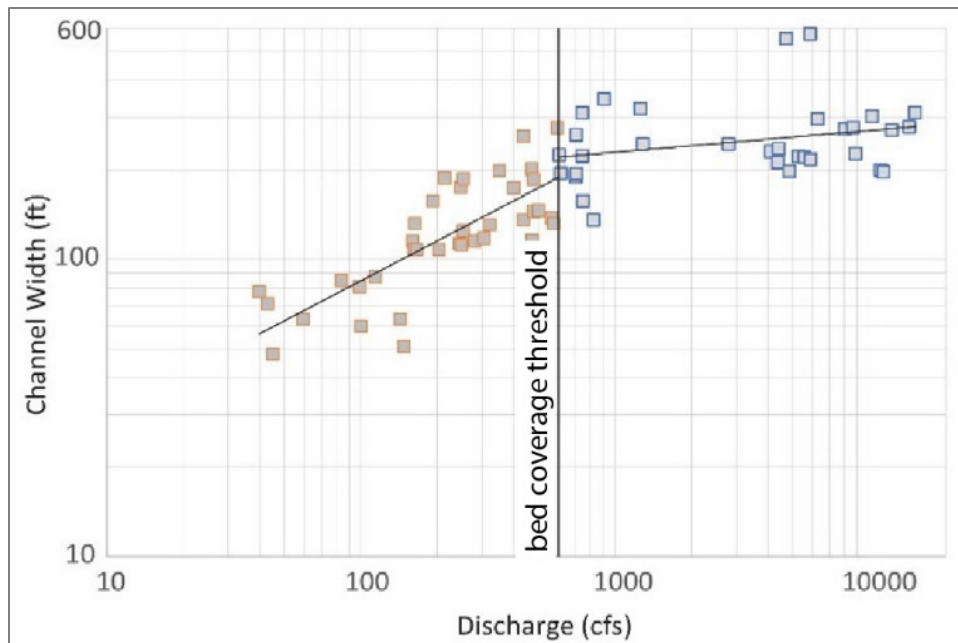


Figure 12. Field measurements from the USGS Deerlodge Park stream gage record between 2012 and 2022. Channel width increases rapidly with increasing discharge until ~600 cfs, when channel width then increases more slowly. Width increases more rapidly as the flows expand to cover the channel bed. Once the channel bed is covered, depth increases faster than width. Our understanding of these flow-channel dynamics formulated at the USGS gage cross-section were verified by satellite image analysis.

Bar Coverage and Plant Establishment. The Plant Establishment resource metric was calculated as the minimum Bar Coverage metric in a 2-year moving window. As such, the resource metrics are less than the hydrograph metrics (see Figure 13).

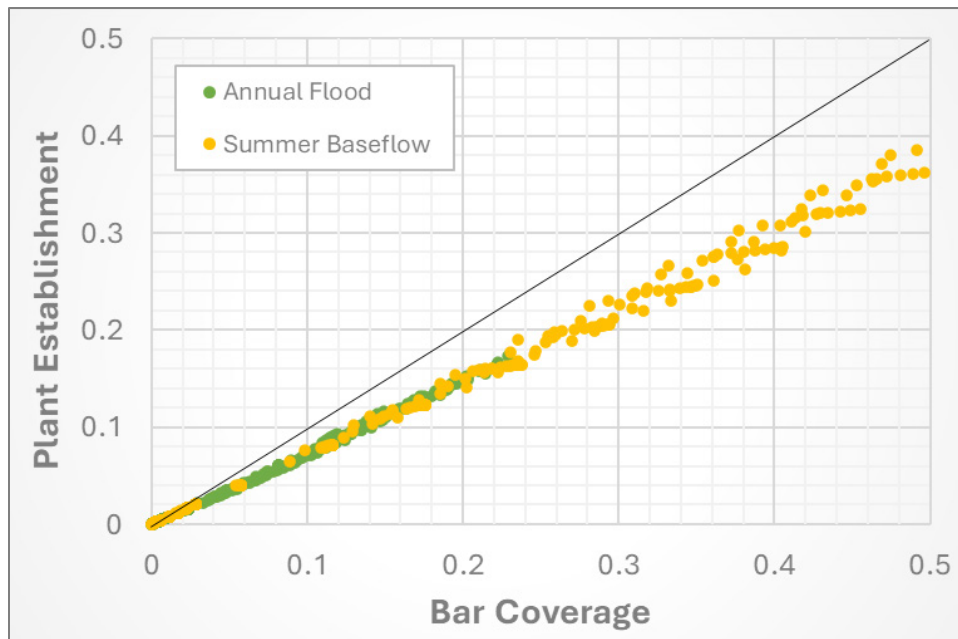


Figure 13. Relationship between the Plant Establishment resource metric and Bar Coverage hydrograph metric applied to the two seasonal periods that occur during the growing season, Annual Flood and Summer Baseflow. Black line is a 1:1 line between the hydrograph and resource metric.

Seasonal Average and Water Temperature. We identified a relationship between the number of days during the Summer Baseflow period for which water temperature exceeded 30°C and the average discharge for that same period for the years 2003 to 2022 (Figure 14). The average daily temperature was defined as the average of the daily minimum and maximum values measured at the Deerlodge Park USGS stream gage. This relationship exhibits a threshold at 600 cfs; for years in which the Seasonal Average discharge was greater than 600 cfs, there are no days for which the water temperature exceeded 30°C, whereas years in which the average was less than 600 cfs experienced water temperatures that exceeded 30°C. We used the upper limit of the number of days, which was greater for an increasingly smaller Seasonal Average discharge. According to this relationship, the Yampa will experience about 17 days (out of the 109 in the Summer Baseflow period) above 30°C as average flows are depleted to near zero. The resource metric Water Temperature ranges between 0 and ~0.5 (Figure 15).

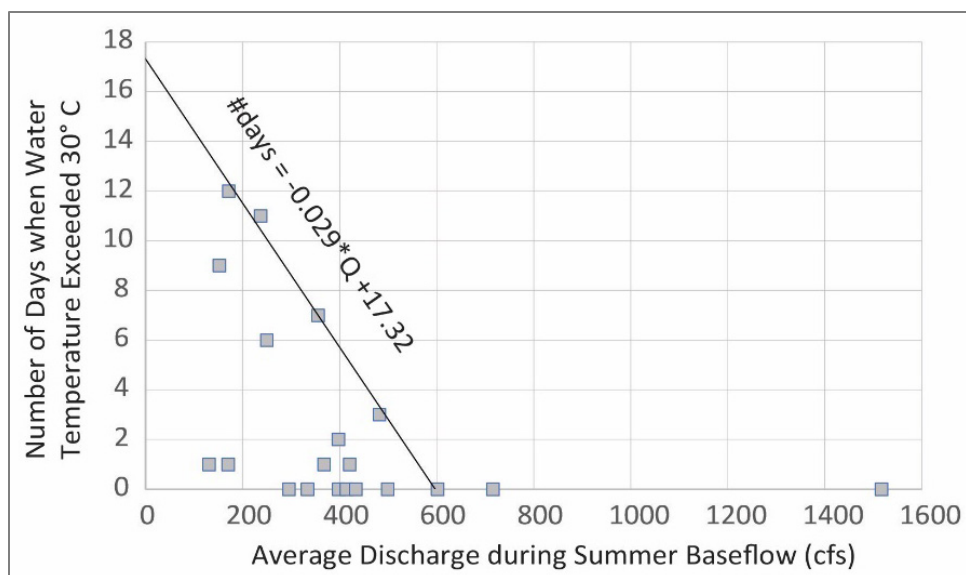


Figure 14. Relationship between Seasonal Average discharge during the Summer Baseflow period and the number of days within that year when average water temperatures exceeded 30°C. Daily min and max water temperatures reported at the USGS stream gage in Deerlodge Park were used for the years 2003 to 2022.

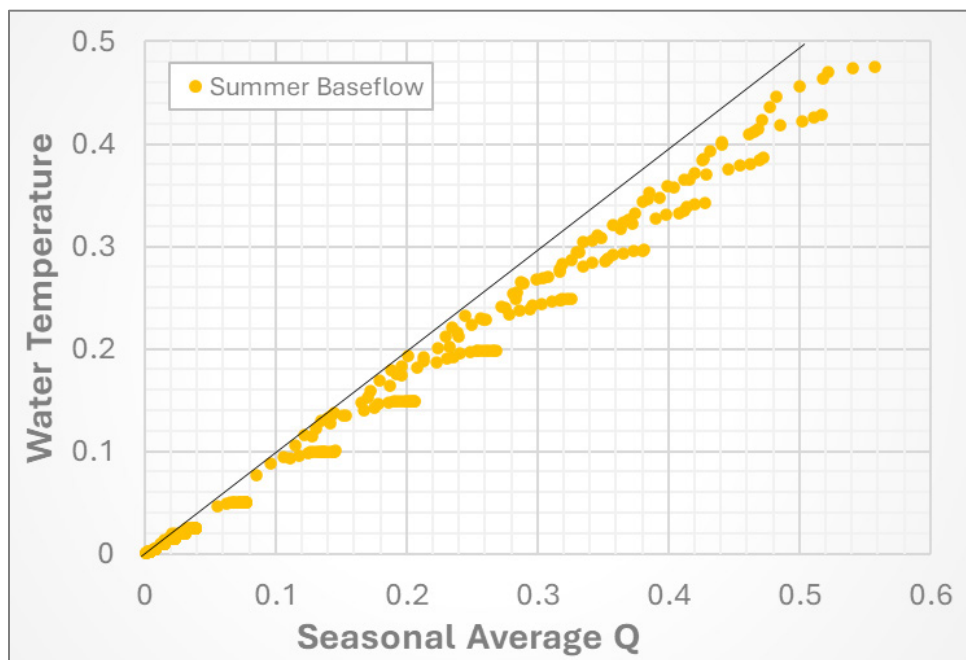


Figure 15. Relationship between the Water Temperature resource metric and Seasonal Average Discharge hydrograph metric applied to the Summer Baseflow period. Black line is a 1:1 line between the hydrograph and resource metrics.

Flood Volume and Sediment Load. To relate the hydrograph metric Flood Volume to the estimated impact to the sediment load, as determined by the Sediment Load resource metric, we developed a relationship between the estimated total sediment load and the volume of water in excess of the Q_{MAF}

threshold (2040 cfs). We used the Elliott and Anders (2005) sediment rating relation to predict daily total sediment loads for the full historical record. Annual sediment loads were then summed for the Annual Flood and Early Runoff periods and associated with the volume of water in AF, during that period, that exceeded 2040 cfs (Figure 16). To improve the accuracy, the relationship between volume and sediment load was segmented into three relationships based on annual flow volumes less than 5×10^5 AF, between 5×10^5 AF and 10×10^5 AF, and greater than 10×10^5 AF (Figure 16). All annual flow volumes for the Early Runoff period fell in the less than 5×10^5 AF category, and we used observations for both the Annual Flood and Early Runoff period in developing this relationship. Continuous sediment monitoring at USGS gages on the Yampa, Little Snake and Green Rivers in and around DINO by the Grand Canyon Monitoring and Research Center (GCMRC) has suggested that sediment loads past the Deerlodge Park gage are highly variable in time, and responsive not only to streamflows, but also bed grain sizes and ultimately to the history of sediment delivery from the Little Snake River (Topping *et al.*, 2018). To evaluate accuracy of our discharge-driven approach to estimating shifts in sediment loads, we compared the Elliott and Anders (2005) estimates of total load to those estimated by GCMRC from 2013 to 2022 (Figure 17) and found that the estimates are reasonable. Generally, the Elliott and Anders (2005) approach over-estimated the Early Runoff period loads and underestimated the Annual Flood period loads. The Sediment Load resource metric nearly tracks with the Flood Volume hydrograph metric in the Annual Flood period but is slightly less during the Early Runoff period (Figure 18).

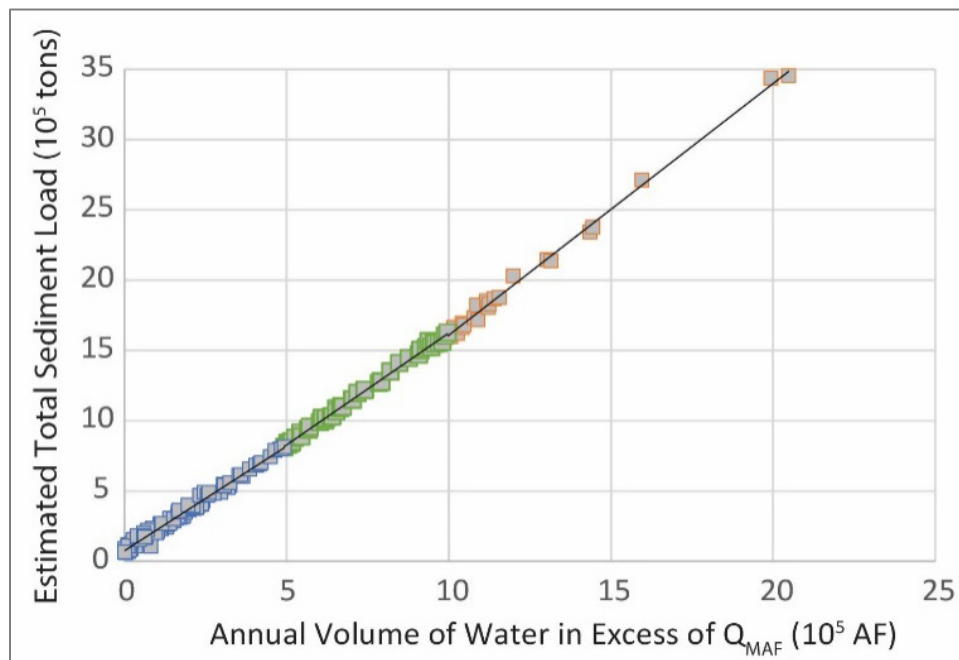


Figure 16. Relationship between the annual volume of water above the Q_{MAF} threshold and the estimated total sediment load, based on the Elliott and Anders (2005) rating curve, calculated for the Early Runoff and Annual Flood periods separately. We used this relationship to translate the Flood Volume hydrograph metric to the Sediment Load resource metric.

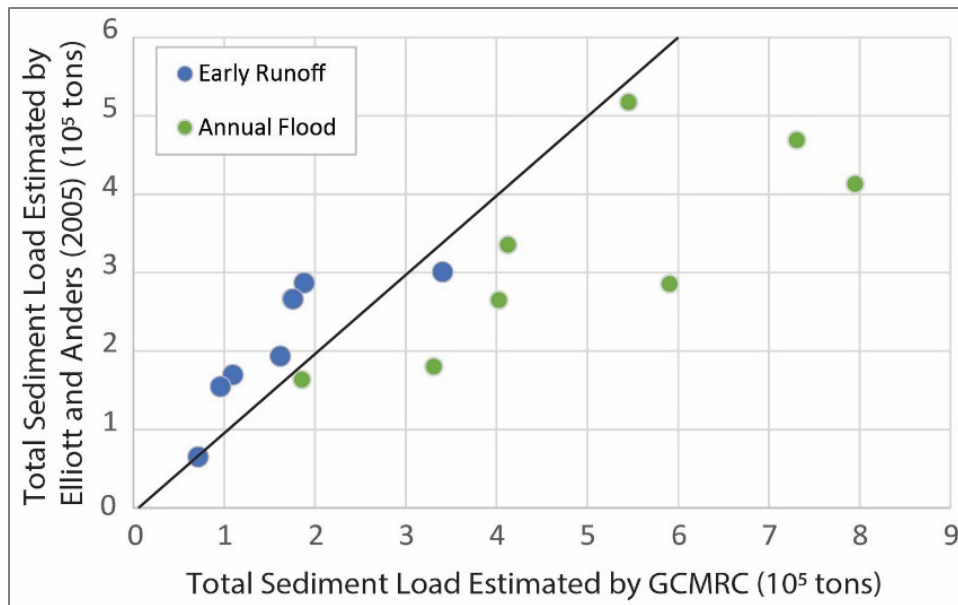


Figure 17. Relationship between total sediment load as estimated from continuous measurements at the USGS Deerlodge Park stream gage and our estimate of total sediment load using the Elliott and Anders (2005) rating curve for the Early Runoff and Annual Flood periods. GCMRC is the Grand Canyon Monitoring and Research Center.

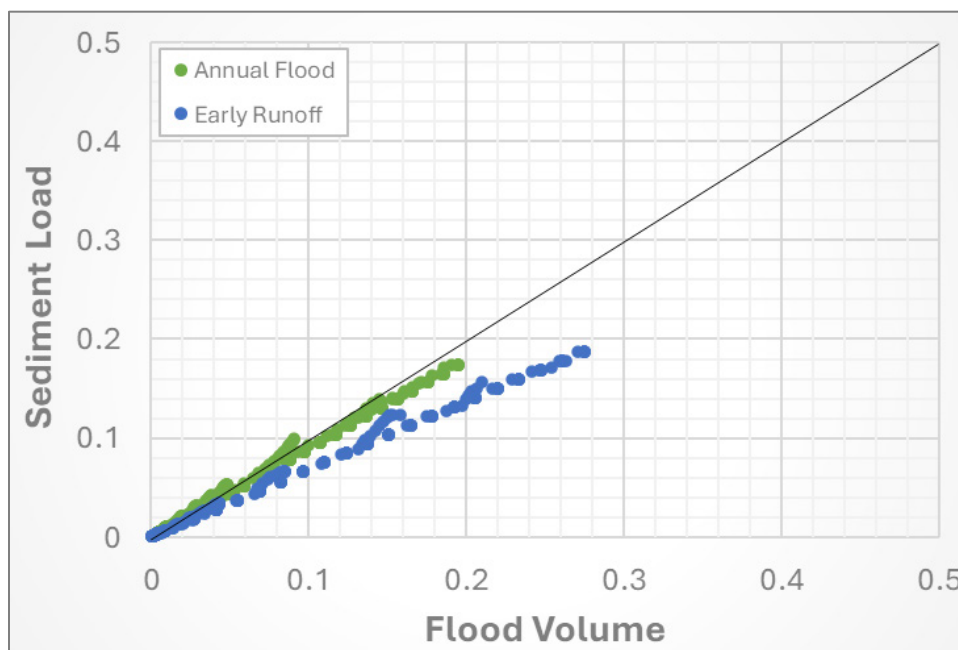


Figure 18. Relationship between Sediment Load resource metric and Flood Volume hydrograph metric applied to the two runoff periods. Black line is a 1:1 line between the hydrograph and resource metric.

Flood Duration and Geomorphic Work. Channel change is dominated by the effects of infrequent high flows, and the discharge transporting the greatest fraction of the annual sediment load is defined as the effective discharge (Andrews, 1980). We assumed that there was a direct relationship between

the ability of the annual flood to perform geomorphic work and the duration of the snowmelt flood above the effective discharge (10,000 cfs). As such, the Geomorphic Work resource metric was directly related to the Flood Duration hydrograph metric (Figure 19).

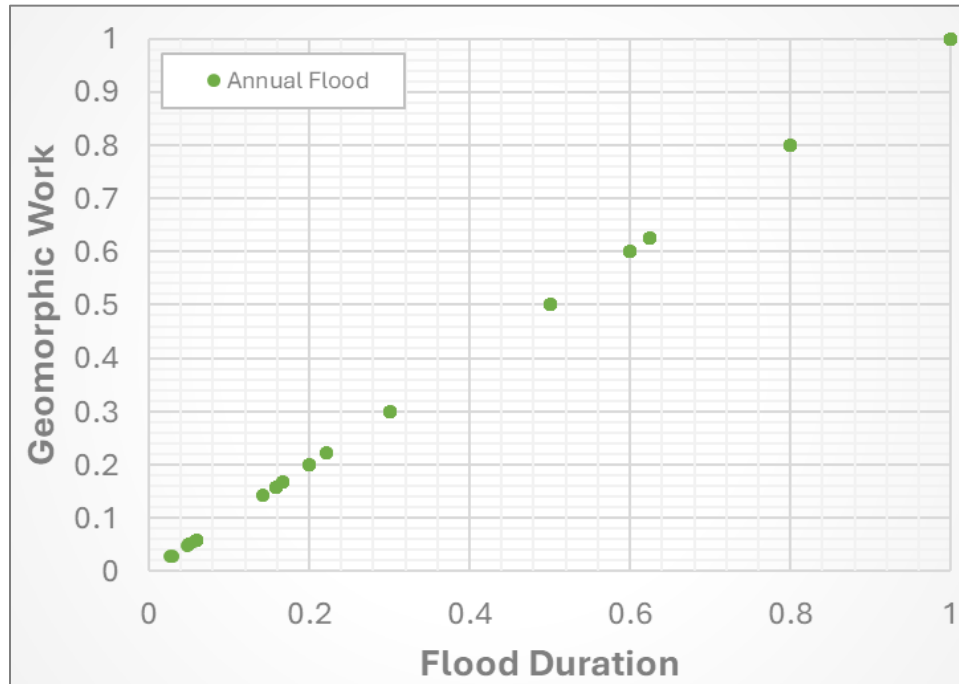


Figure 19. Relationship between Geomorphic Work resource metric and Flood Duration hydrograph metric applied to the Annual Flood period.

Flood Peak and Channel Width. Because channel width generally scales to flood peak, we assumed that a decrease in the flood peak would correspond to a proportional change to the channel size (Figure 20). We related the change in peak flow (measured as a proportion between the alternative and historical hydrograph) to a proportional change in channel width using a simple ratio of the hydraulic geometry relationship between Q and W, raised to the 0.5 power:

$(Q_{\text{alternative}}/Q_{\text{historic}})^{0.5} = (W_{\text{alternative}}/W_{\text{historic}})$, where Q_{historic} is the peak discharge of the historical hydrograph, $Q_{\text{alternative}}$ is the peak discharge of the alternative hydrograph, W_{historic} is the historic width, and $W_{\text{alternative}}$ is the channel width that might be expected given the change in the peak discharge.

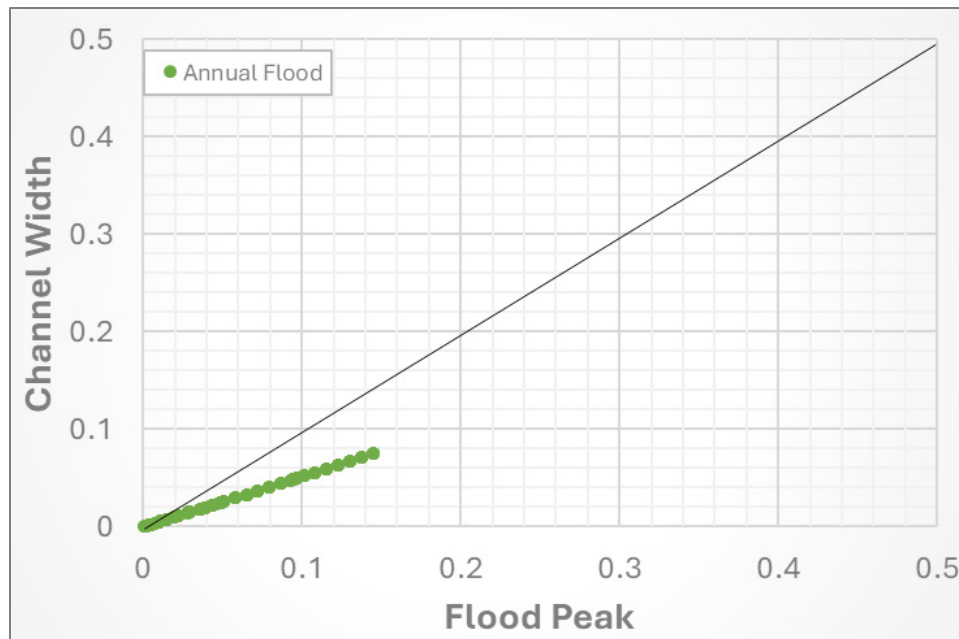


Figure 20. Relationship between Channel Width resource metric and Flood Peak hydrograph metric applied to the Annual Flood period. Black line is a 1:1 line between the hydrograph and resource metric.

Appendix E: Response Surfaces for Each Resource Metric

Figure 21 shows the response surfaces for each resource metric by seasonal period.

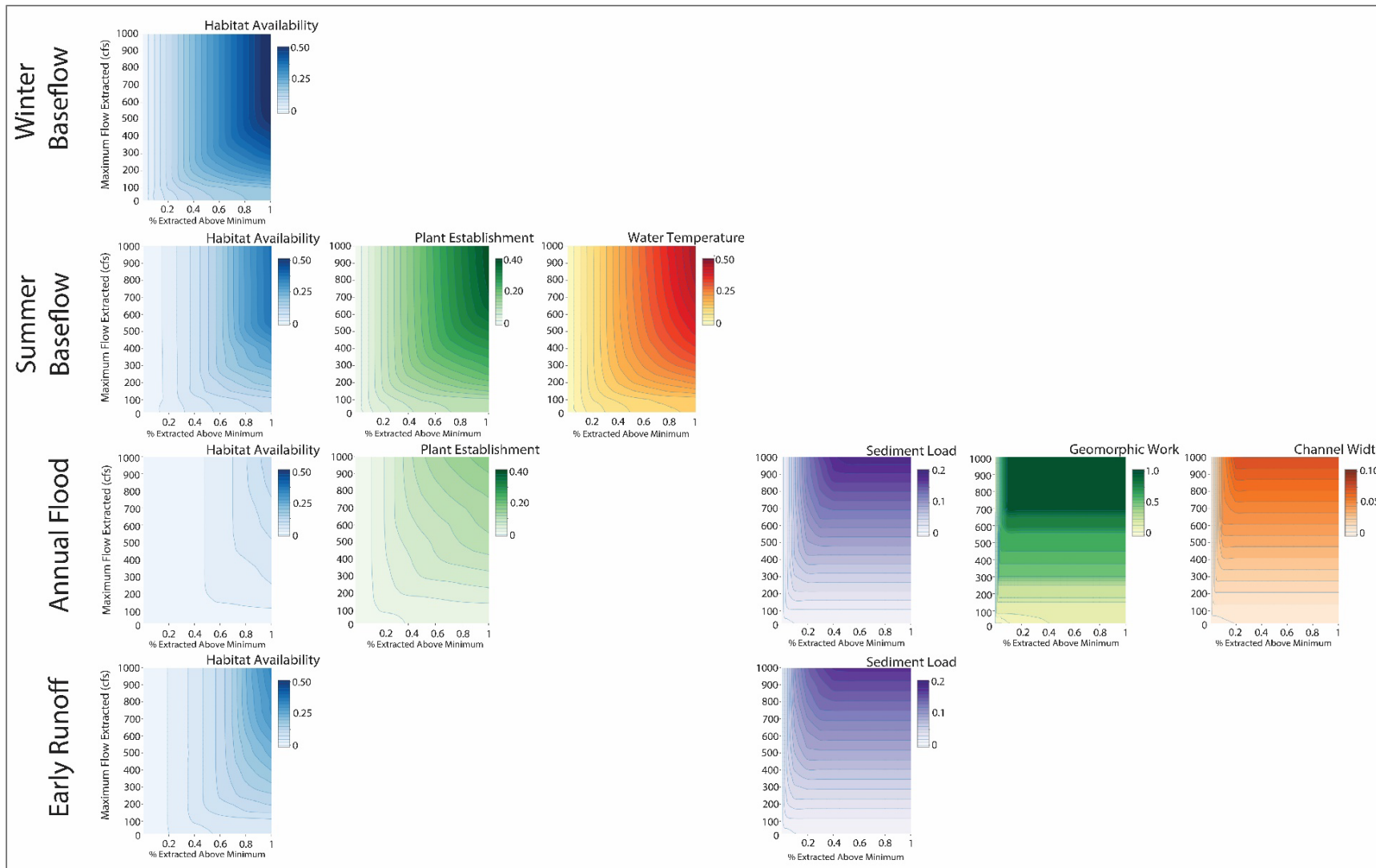


Figure 21. Resource metric response surfaces for the 350 extraction scenarios. Note that the contour ranges are the same within a given resource metric but vary between metrics to better highlight trends. Colors represent values of resource metrics as indicated in the key.

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