Decision Support for Environmental Flow Management on the Fryingpan River

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1 Purpose and Need

The Fryingpan River, located west of Basalt, Colorado, is widely known for its Gold-Medal trout fishery and stunning scenic beauty. Ruedi Reservoir impounds the Fryingpan River 15 miles upstream of Basalt. Water releases out of Ruedi Reservoir support a renowned trout fishery, hydropower generation for the City of Aspen, and water supply for downstream municipalities and agricultural water users. Constraints on water availability and the timing of inflows to the reservoir make it difficult to manage releases to optimally support each downstream use at all times of the year. This is particularly true in dry years. In times of water scarcity, water stored in Ruedi Reservoir is primarily used to deliver water for irrigated agriculture and habitat requirements for Threatened & Endangered fish species on the Colorado River near Grand Junction. In these years, modification of the Fryingpan River's hydrological regime can be significant.

Reservoir operations in the summer of 2018 highlighted the need for a more strategic approach to managing releases from Ruedi Reservoir. Recent dialog between Roaring Fork Conservancy (RFC), the Ruedi Water and Power Authority (RWAPA), City of Aspen (Aspen), Colorado Water Conservation Board (CWCB), Colorado River Water Conservation District (River District), and the Bureau of Reclamation (USBR) resulted in a commitment from all parties to participate in ongoing cooperative dialog about optimization of water releases to support multiple uses. RFC requires assistance characterizing optimal water management approaches for supporting aquatic life across seasons and different hydrological year types.

The tools presented here will help ensure that RFC is well-positioned to advocate for river health needs on the Fryingpan River. This report includes 1) a summary previous studies linking streamflow to ecosystem health, 2) a conceptual model linking hydrological characteristics to specific ecosystem functions or variables, and 3) a pair of ecological decision support tools that aim to support RFC's advocacy for maintenance and protection of aquatic and riparian ecosystems. The decision support tools developed and presented here aim to encourage dialog between RFC, RWAPA, Aspen, CWCB, the River District, and USBR in a way to produce a more informed water management decision-making process on the Fryingpan River across year types and into an uncertain future where climate change-induced alteration of regional hydrology may necessitate new operational strategies and release schedules for Ruedi Reservoir.

2 Background

Riverine ecosystems are adapted to long-term characteristics of hydrologic behavior and other bio-geophysical factors. Broad patterns of precipitation and topography largely determine a river's flow regime. In turn, fluvial ecologists generally treat flow regime as the "master variable" exerting an outsized influence on riverine ecosystem form and function. Operation of reservoirs alters the hydrological behavior of downstream streams and rivers.

The interrelationships between physical attributes of the river system affected by reservoirs—including hydrological regime behavior, sediment transport, thermal regimes, and water chemistry—and river health indicators of interest to RFC like trout recruitment, presence and diversity of aquatic macroinvertebrate communities, blooms of didymo (a.k.a. snot rock), and formation of anchor ice is complex. Studies conducted over the previous 80 years explore various aspects of this complexity.

Previous studies reviewed during this effort explore the interplay between streamflow behavior, the native fishery, the introduced sport fishery, American Dippers, benthic invertebrates, anchor ice, and didymo blooms. The (then) Division of Wildlife (CDOW) began studying the Fryingpan River in 1943, before the construction of the reservoir. CDOW also completed post-reservoir Fryingpan River studies each year from at least 1972 to 2000. Each time the U.S. Bureau of Reclamation (USBR) proposes a change in Ruedi operations, it conducts an environmental study. Several of these are available from the 1980s and 1990s. Recently, the Roaring Fork Conservancy has funded investigations into the health of the Fryingpan as it relates to several river attributes known to influence aquatic and riparian ecosystem health. This compendium of work (Appendix A) identifies numerous relationships between the timing, duration, and magnitude of reservoir releases and the ecological characteristics of the Fryingpan River corridor. Construction of Ruedi Dam drove numerous hydrological changes in the Fryingpan River below Ruedi Reservoir. Corresponding changes to aquatic habitat and chemical changes to the waters of the Fryingpan River are also observed. Finnell (1977), Ptacek (2003) and others summarize of the effects of reservoir management on the Fryingpan River:

- Altered Hydrologic Regime Behavior
    - Baseflows have increased
    - Fluctuations in flows have increased
    - Peak flows have decreased
    - In some years, peak flows have shifted forward from late spring/early summer to late summer/early fall
- Altered Water Temperature
    - Winter water temperatures have increased
    - Summer water temperatures have decreased
- Altered Water Quality
    - Reservoir releases are characterized by higher pH, hardness, and conductivity than inflows to Ruedi Reservoir
- Altered Aquatic Communities
    - The amount of suitable habitat for adult trout has increased
    - Rainbow trout spawning is limited by colder temperatures
    - Brown trout spawning is delayed by altered fall temperatures
    - Average trout size has increased
    - Sculpin are absent in the reaches immediately below the dam
    - Macroinvertebrate densities have increased

Figure 1. View looking upstream on the Fryingpan River toward Ruedi Reservoir (Photo Credit: USBR)

Synthesis of the available scientific and resource management studies makes it clear that managing the river in one manner will benefit some species or ecosystem attributes more than others. For example, CDOW found that in the Fryingpan River, optimum flows for adult rainbow trout were around 250 cubic feet per second (cfs) year-round. (Nehring 1988). Conversely, optimum flows for brown trout at any stage in their life cycle were identified closer to 100 cfs. (Nehring 1988). A literature review uncovered several such tradeoffs. While minimum instream flows and fish habitat maintenance flows have been studied extensively on the Fryingpan River, little is known about relationships between the timing and magnitude of annual peak flows and sediment transport. Neither is much quantitative evidence presented in the literature linking late-summer reservoir releases to exceedances of water temperature standards on the lower Fryingpan River or the lower Roaring Fork River. A comprehensive effort to unify various sources of historical information on environmental flows and conduct several new data analyses was, therefore, required to provide RFC with guidance on optimal reservoir release strategies.

2.1 Hydrology and Reservoir Management

Ruedi Dam was completed in 1968 on the Fryingpan River 14 miles above the confluence with the Roaring Fork River. This resulted in the inundation of 7 miles of the Fryingpan River and flooding of 1,000 surface acres. The capacity of the reservoir is 102,360 acre-feet. Construction and operation of Ruedi Reservoir and the completion of a system of transmountain diversions in the 1970s via the U.S. Bureau of Reclamation (USBR) Fry-Ark Project altered hydrological regime behavior on the Fryingpan River below the dam. Transmountain diversion of water from the tributaries to the Fryingpan above Ruedi Reservoir and storage of peak flows in the reservoir itself significantly reduce streamflows during the summer months (Figure 2). Releases of water from the reservoir during the late-summer, fall and winter months to support downstream water uses increases streamflows in those periods when compared to the natural condition.

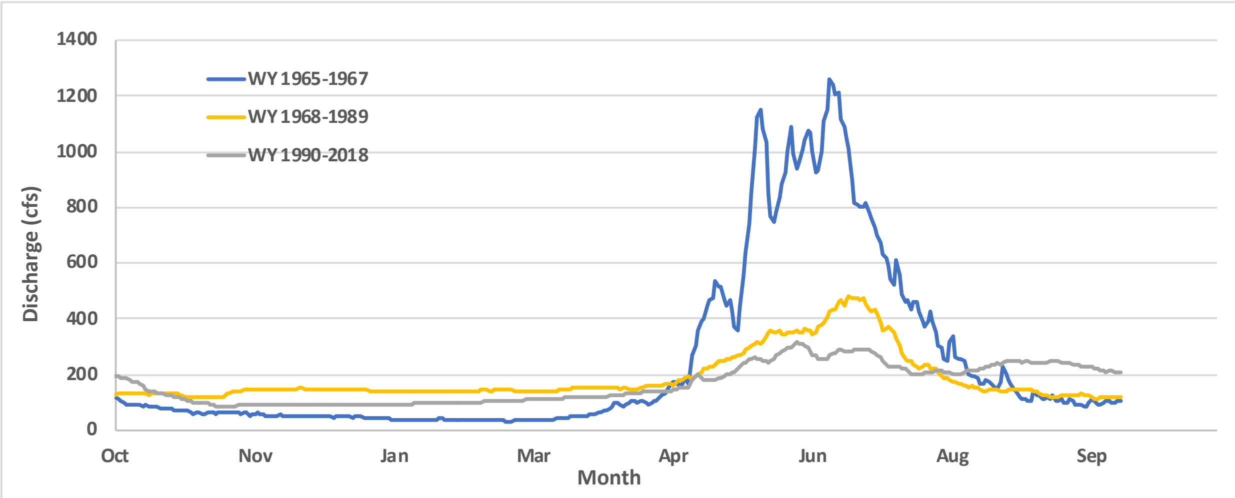


Figure 2. Mean daily flows for the Fryingpan River below Ruedi Reservoir (USGS gage 09080400) for the periods before Ruedi Dam (WY 1965-67), construction of the dam until the 1989 change in management strategy (WY 1968-89) and 1989 to present (WY 1990-2018).

Changes in streamflow behavior following construction of Ruedi Reservoir and during subsequent years of operation of the dam and the Fry-Ark project were assessed using the *FlowScreen* library in the *R* statistical computing environment. Daily average streamflow data was retrieved for the United States Geological Survey (USGS) streamflow gauge on the Fryingpan River below Ruedi Reservoir (USGS 09080400). The period of record for that gauge extends from 1964-2020. The limited period of record prior to completion of the reservoir might bias results but provides some ability to compare characteristics of natural streamflow behavior to the managed conditions observed in the Fryingpan River today. Given that this hydrological review is for background purposes only, a more rigorous analysis involving the simulation of natural flows on the Fryingpan River was deemed unnecessary.

Exploration of analysis results illustrates expected impacts of reservoir operations on streamflow behavior in the Fryingpan River (Figure 3). Statistically significant change is observed for several hydrological metrics following completion of dam construction. Annual maximum baseflows decreased after reservoir construction. Annual minimum baseflows and the 7-day minimum flow increased due to late season reservoir releases. Peak flow (i.e. Annual Maximum Series), the 80th percentile of annual flow magnitude (Q80), and the 90th percentile of annual flow magnitude (Q90) decreased due to water storage during snowmelt runoff. The date of annual maximum flow became much more variable after USBR completed the Round II Water Sale (USBR 1989).

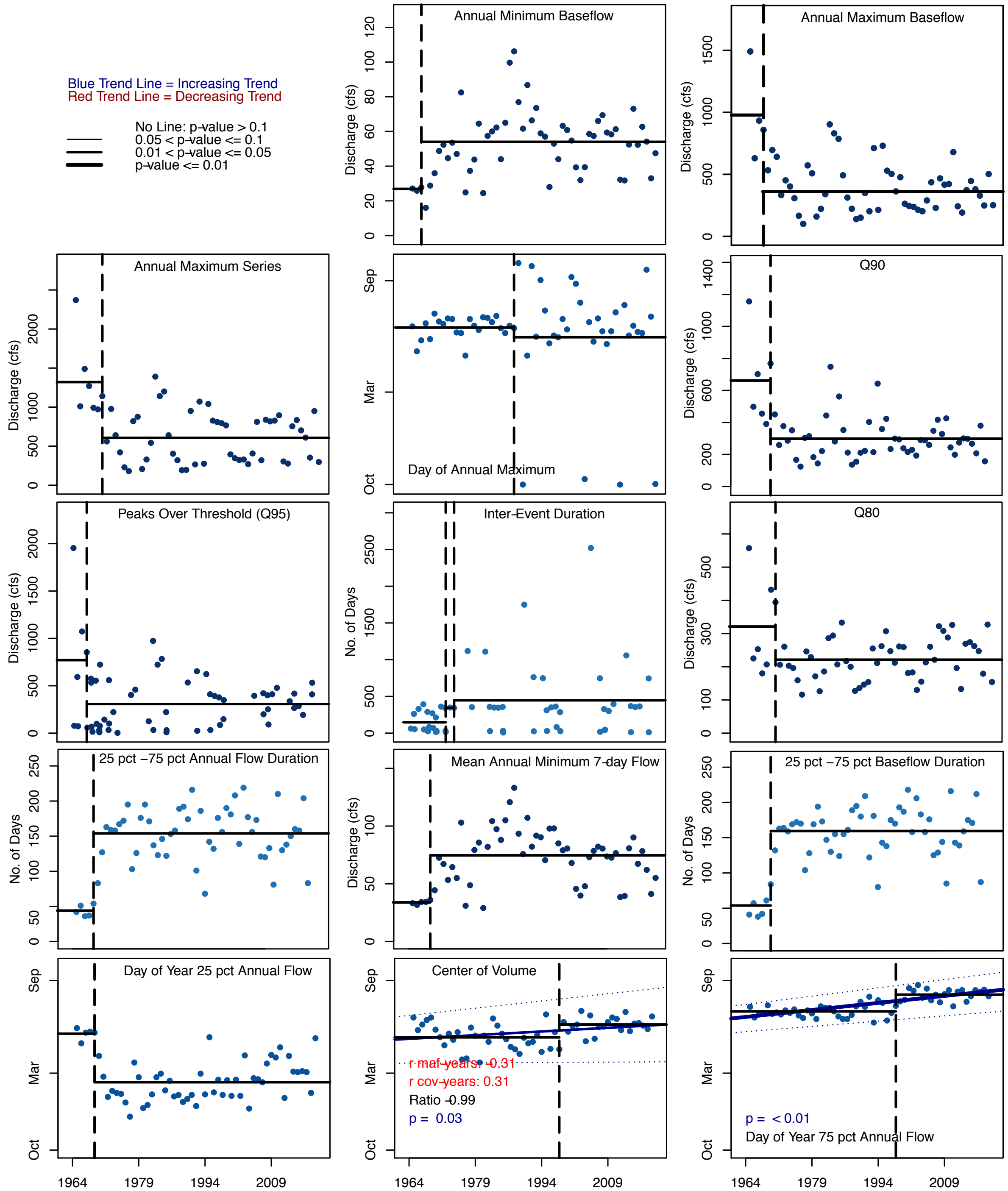


Figure 3. Change point and trends analysis of streamflow behavior on the Fryingpan River below Ruedi Reservoir for the full period of record (1964-2020). Statistically meaningful changes in behavior are denoted with vertical dashed lines. Mean behavior before and after each change point is indicated with horizontal black lines. Change points tend to coincide with completion of Ruedi dam in 1968, development of new operational strategies for the reservoir in the late 1980s and the onset of long-term drought conditions in the early 2000s.

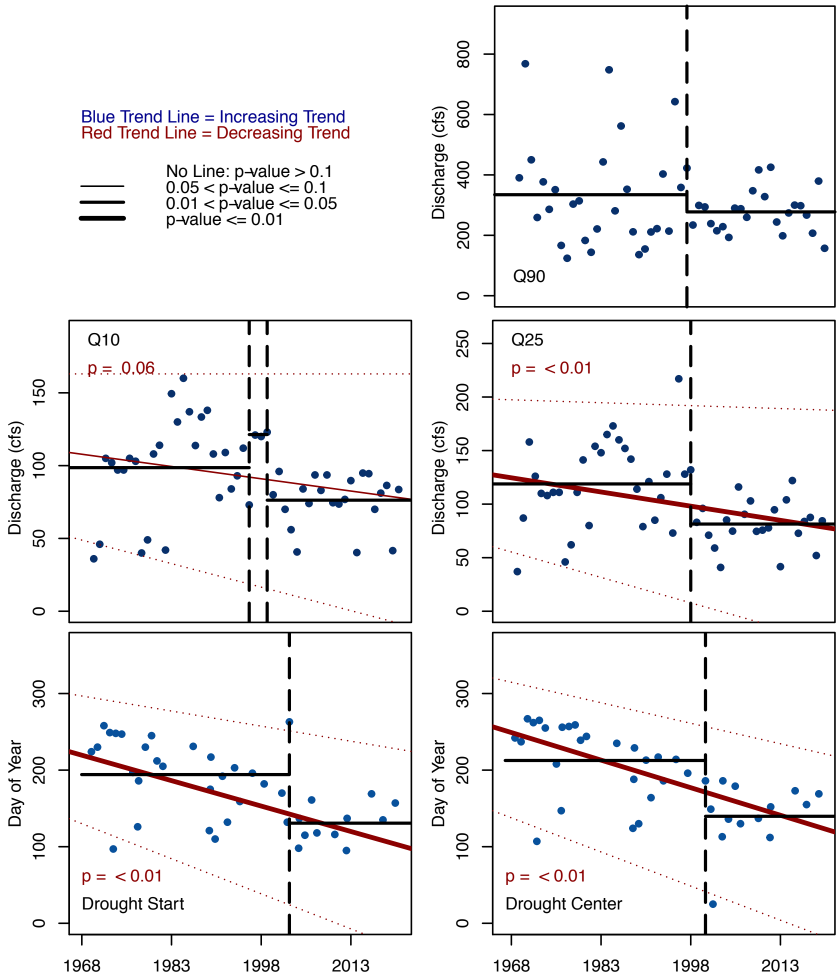


Figure 4. Change point and trends analysis of select streamflow behaviors on the Fryingpan River below Ruedi Reservoir for the period following completion of Ruedi Reservoir (1969-2020). Statistically meaningful changes in behavior are denoted with vertical dashed lines. Mean behavior before and after each change point is indicated with horizontal black lines. Downward trends are indicated as solid red lines. Change points tend to coincide with the onset of long-term drought conditions in the early 2000s.

The analysis of hydrological behavior described above was repeated for the period of record after dam construction in order to identify significant trends or change points on the Fryingpan River during periods when reservoir management affects flows. Results from this analysis indicate several important trends and statistically significant change points (Figure 4). High flow magnitudes (Q90) and low flow magnitudes (Q10, Q25) decreased over the period with a significant change point identified in the early 2000s with the onset of prolonged drought conditions. Statistically significant downward trends are observed in the 10^{th} and 25^{th} percentiles of annual flow magnitude (Q10 and Q25, respectively). The onset of droughts, defined here as a consecutive 15-day period between April and September when flows are below the 20^{th} percentile of mean daily streamflow magnitudes, is trending earlier in the year. The observed changes in streamflow behavior through time are expected to alter the characteristics of aquatic and riparian ecosystems along the river corridor below Ruedi Reservoir.

2.2 Hydro-Ecological Characteristics of the Fryingpan River

Springtime (March-May) in the Fryingpan watershed is associated with the melting of winter ice and spawning season for rainbow trout. During this period, it is critical that flows stay low enough for rainbow trout to build redds but high enough to ensure sufficient flow over the eggs and maintain access to spawning areas. Rainbow trout spawning is contingent on moderate water temperatures which, in a natural system, would result from melting ice and snow. Colder spring and summer water temperatures in the Fryingpan River below Ruedi are caused by hypolimnetic releases of water from the reservoir. These colder water temperatures likely slow trout growth (Finnel 1997), limit rainbow trout recruitment (Nehring 1982, Ptacek 2003), and limit macroinvertebrate species diversity (Rees 2004). Sculpin abundance is severely limited in the reaches below the dam. This issue has not be studied extensively on the Fryingpan but similar patterns on other Colorado streams below dams suggest that hydrological alteration might be the cause.[1]

Towards the end of spring, flows in headwaters streams begin to increase in advance of the runoff peak. The magnitude of peak annual flows plays a vital role in promoting the quality of the aquatic habitat and maintaining channel forms. High flows mobilize both coarse and fine sediment on the riverbed, inundate riverbanks with water and nutrients, and transport large woody debris and other riparian organic matter along the river corridor. Sediment mobilization is key to maintaining both the river channel form and the quality of the substrate on the riverbed. In years when high flows do not occur due to low precipitation or increased reservoir storage, fine sediment may accumulate in interstitial spaces between larger clasts on the river bottom in reaches closer to Basalt. Accumulating fine sediment leads to "embeddedness", or a resistance of sediment to movement by biota or inorganic means. Relatively frequent high flows are needed to prevent embeddedness and bed immobility. Highly embedded substrates and interstitial spaces clogged with fine sediment can reduce the quality of spawning habitat for trout and degrade habitat for benthic macroinvertebrates—an important food source for fish and American Dippers (Malone 2014). Notably, a lack of sufficient sediment delivery to reaches immediately below the dam likely lead to some amount of bed armoring as small particles are scoured away by high flows and never replaced. Bed armoring has a detrimental impact on aquatic habitat similar to in quality and degree to embeddedness.

In addition to flushing fine sediment, high flows mobilize gravel-sized and larger sediment on the riverbed. Algae and diatoms often accumulate on larger sediment that is not mobilized. If sediment is not mobilized for several sequential years, excessive algal growth can occur. Mats of algae can render bed substrate inaccessible to benthic macroinvertebrates, fish, and American Dippers. The classic example of this phenomenon is the spread of *Didymosphenia geminate*, a freshwater diatom commonly referred to as "didymo". Blooms of didymo are noted in mountain streams across the Rocky Mountains. The Fryingpan River has experienced didymo outbreaks in the past 20 years as peak flows have decreased and the algae has spread between stream reaches via angler activity. CDOW found the reduction in peak flows (Finnel 1977) and lower turbidity (Finnel 1972) lead to an increase in algae production downstream of Ruedi.

[1] Personal communication with CPW biologist, Kendall Backich.

High flows help maintain channel form by mobilizing sediment and vegetation on streambanks. Reservoir storage typically has a smoothing effect on the hydrograph of downstream river segments—reservoir management tends to truncate annual peak flow magnitude and increase base flow magnitude. This change is noted in the hydrological assessment of streamflow behavior below Ruedi Reservoir. The observed shift in the distribution of flow across a water year can lead to vegetation encroachment on previously active surfaces, channel narrowing, and reduced flood conveyance capacity in channels with less than 1.5% gradient (Wesche, 1991; Gordon and Meentemeyer, 2006). Vegetation is more likely to establish adjacent to the channel without high annual flow events, leading to reinforcement of streambanks and channel simplification.

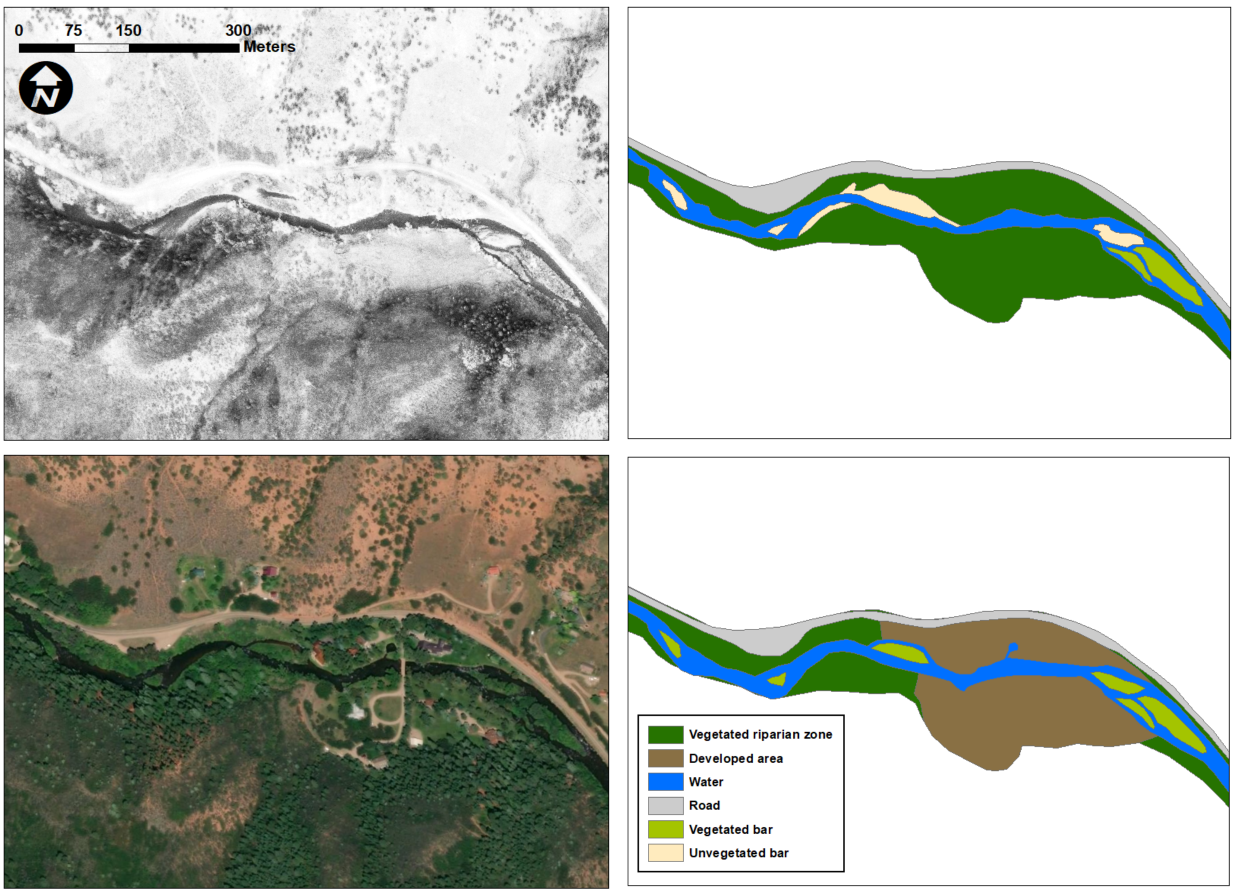


Figure 5. Comparison of aerial imagery and interpretations of land cover from 1962 and 2015 just downstream of Downey Creek.

A comparison of aerial images collected in 1962 and 2015 permits a qualitative assessment of change in channel dynamics following dam construction (Figure 5). Several differences in channel and riparian characteristics are evident in the two images. The first is the development of the Fryingpan River corridor through home construction and landscaping. Many medial bars that were unvegetated before the construction of Ruedi Reservoir are now densely vegetated islands. Islands observed in the river channel in the 1962 image are in almost the same location in 2015. Some deformation or migration of these features would be expected in a natural system. The conversion of unvegetated bars to densely vegetated areas is most likely the result of truncation of peak flows. In unregulated systems, high annual flows inundate low-lying bars on streambanks and in the middle of the channel. These high flows mobilize coarse and fine sediment and prevent vegetation growth, which creates a dynamic fluvial corridor. Since construction of Ruedi Reservoir in 1968, peak flows have been much lower than the historic peak flows. This is especially true in the period since 1989. Before 2019, peak flows had not exceeded 1,000 cfs since 1997.

The vegetative colonization of medial bars and streambanks has mixed impacts on ecosystem function. Colonization of open gravel bars by vegetation reduces the amount of foraging area for avian birds such as the American Dipper (Cubley, 2020), while also reducing riffle area in times of intermediate flow (Venarsky et al., 2018). In general, persistent vegetation colonization of bars reduces the amount of physical complexity within the riparian corridor (Tonolla et al. 2020), which may reduce the number of terrestrial and aquatic ecological niches present in the system. However, the spread of vegetation increases the shaded area of the stream and enhances delivery of carbon and organic matter to the water column, which can benefit numerous macroinvertebrate and fish species. These opposing effects make prediction of the impacts of vegetation encroachment along the Fryingpan River difficult.

The timing of peak flows is also a critical control on the condition and characteristics of riparian vegetation. On the Fryingpan River, peak flows typically occur between late May and mid-July—a natural hydrological pattern in snowmelt dominated watersheds. However, in low water years, peak flows in the Fryingpan River below Ruedi Reservoir may be delayed until much later in the summer season. Peak flows in the river during the 2002 and 2012 drought years occurred in November and October, respectively. This shift in peak flow timing may impact riparian vegetation as it fails to coincide with the natural period of seed release for woody vegetation. This effect is demonstrated by the Recruitment Box conceptual model presented by Mahoney and Rood (1998) (Figure 6).

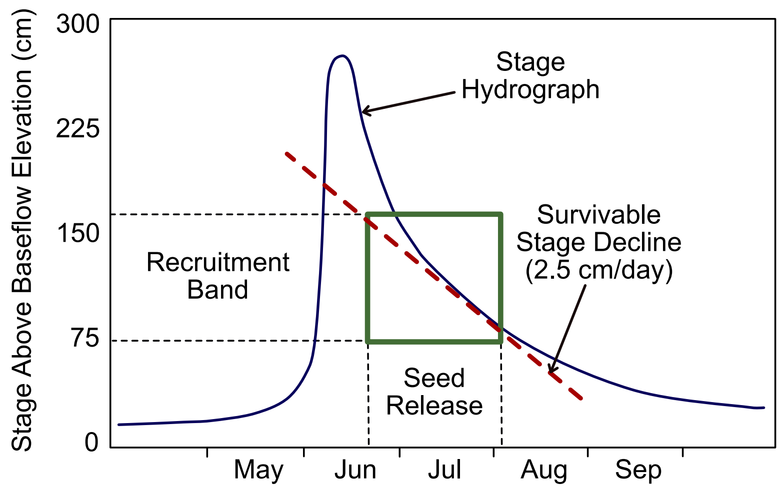


Figure 6. Recruitment box conceptual model (Mahoney and Rood, 1998) indicating hydrological controls on establishment of woody riparian vegetation. Peak flows that occur late in the summer and fail to coincide with the period of seed release may limit riparian recruitment over time.

Malone (2014) noted that the reduction in peak flows following reservoir construction likely diminished the quality of riparian habitat needed by populations of American dipper.
If reductions in peak flow magnitude are effecting riparian recruitment along the Fryingpan River, they are difficult to observe without intensive local study. It is possible that any reductions

in annual recruitment rates are partially masked by the encroachment of vegetation onto medial bars following construction of the reservoir. The impacts of reduced overbanking flows on recruitment of woody vegetation may become more apparent over the next 30-50 years as vegetation that recruited in the years immediately following dam construction transitions into decadent old growth canopy.

Snowmelt runoff impounded by Ruedi Dam in the early summer is released to the Fryingpan River throughout the late summer, fall and winter months. Reservoir releases increase pool depths and the wetted perimeter of the channel. Thus, operation of Ruedi Reservoir tends to increase late-summer and fall flows in a manner that enhances habitat quality and availability for adult rainbow trout and for brown trout of all life stages beyond the natural condition (Nehring 1988).

In temperate climates such as the Colorado Rockies, winter flows often receive little attention. However, the winter period frequently serves to promote or limit critical ecosystem functions. Winter flows are generally much lower than flows during the rest of the year due to a lack of water input to the system. Low flows coincide with low water velocities—conditions that are advantageous for incubating brown trout eggs (Nehring 1988b). Low velocities and relatively warm water below the reservoir help preserve brown trout eggs throughout the winter and lead to greater reproductive success for brown trout.

The magnitude of winter flows is expected to affect the number and species density of aquatic macroinvertebrates on the Fryingpan River (USBR 1989; Rees 2003). Low velocities and depths seen during winter base flows combined with low air temperature can lead to anchor ice formation. Anchor ice formation has been documented to reduce benthic macroinvertebrate counts on the Fryingpan River, an important food source for aquatic species throughout the year (Miller Ecological Consultants 2006). Scouring of the streambed by anchor ice leads to detachment of bed particles, which disturbs critical benthic macroinvertebrate habitat. The mechanical grinding effect of anchor ice on the streambed may also produce significant mortality among some species of macroinvertebrates.

2.3 Whirling Disease

Whirling disease was introduced to the Roaring Fork River when trout exposed to the parasite were stocked into the river by a private aquaculturist in the late 1980's. Rainbow trout, brown trout and mountain whitefish tested positive for the presence of cranial myxospores between 1994 and 1997. Myxospore burdens in all three species were low. (Nehring, R. Barry et al. 2000). Since then, the incidence and severity of whirling disease has been very low. CPW continues whirling disease control efforts on the Fryingpan.

2.4 Angling and Stocking

Notable human interventions and activities known to affect local ecosystem characteristics include angling, stocking and other aquatic resource management activities. Historically the Fryingpan River had been one of the most heavily fished trout streams in Colorado. Fisheries with high angling pressure often require conservative regulations. Rainbow trout respond better to harvest restrictions than brown trout (Espegren 1990). Poor rainbow trout reproduction observed in the Fryingpan River is offset with regular stocking and with catch-and-release fishing regulations originally imposed in the early 1980s (Anderson 1984, Nehring 1986). USBR studied the impact of fishing days on the health of the Fryingpan's fishery and found that flows greater than 250 cfs benefited the fishery by reducing fishing pressure (USBR 2002).

The fishery is also supported by the introduction of mysis shrimp to the environment. The mysis shrimp was stocked in Ruedi Reservoir in 1970, but first appeared below the dam in 1985 after the completion of a hydroelectric power station (Nehring 1988; Nehring 1991). The availability of the shrimp enhances trout growth in the Fryingpan River, especially in wet years (Espegren 1990; Nehring 1994). During periods following below-normal precipitation, mysis shrimp availability in the Fryingpan River declines. Sharp declines in rainbow and brook trout populations are observed in these periods in the river (Nehring 1994). Nehring (1999) theorized that this pattern is driven by brown trout becoming increasingly piscivorous as mysis shrimp densities decline.

2.5 Land Use Impacts

Conversion of riparian vegetation to lawn cover and landscaping in some locations along the Fryingpan River reduces the available habitat for riverine species such as the American Dipper while also reducing vegetative shading of the river. Runoff from landscaped properties is expected to contain lawncare products and fertilizers that can impact water chemistry. Riverbanks are stabilized and reinforced in some locations to protect roads, homes and property from fluvial hazards. These stabilization efforts contribute to patterns of channel simplification discussed previously and, thereby, to the alteration of aquatic habitat in discrete locations.

2.6 Conceptual Model of Ecosystem Response to Flows

The body of research and studies generated on the Fryingpan River between the 1940s and the present (Appendix A) supports the development of a conceptual model of ecosystem responses to hydrological regime behavior and streamflow management activities (Figure 7). This conceptual model should encourage conversations about system behavior and collective understanding among stakeholders regarding connections between specific hydrological regime characteristics affected by management of Ruedi Reservoir and the ecological or biological variables important to local communities. For the sake of simplicity, the model includes mostly unidirectional relationships—feedback loops are exploded to reveal intermediate connections between variables. This approach increases the number of variables represented in the system, perhaps increasing its complexity at first glance. However, the primary benefit to the end user is that the model becomes more readable and explicit in its representation of system behavior.

The conceptual model presented here likely differs by degrees from those held by the various investigators who considered Fryingpan River processes over the previous 80 years. However, it affectively aggregates the main ideas presented by each of those individuals. This model focuses on hydrological and biological variables and does not incorporate the entire diversity of human uses and needs for water from the Fryingpan River (e.g. hydropower production for the City of Aspen, revenue generated in the Town of Basalt by angling activities, etc.). Rather it attempts to illustrate how the conditional state of important ecosystem characteristics might respond to reservoir management activities that impact typical spring flows, peak flow timing and magnitude, summer flows, fall flows, and winter flows.

Established quantitative predictive relationships between variables are not common. For example, while some research indicates that flows for multiple days above 700 cfs are effective at reducing the abundance of didymo, no indication is given in the literature regarding the relative effectiveness of 600 cfs or 800 cfs for achieving the same effect. Even for variables like trout habitat where quantitative relationships can be used to link the concept of weighted usable area (WUA) to hydrological regime behavior, clear predictive relationships between availability of WUA and the success of a given species and life stage are not available. Further complicating matters, many variables have dependency structures that link them to multiple parent variables, each of which may be described in terms of quantitatively incompatible measures or units. Such is the case for a concept such as “Fishability”. There is no quantitative measure of the concept, just a general consensus among users about what makes it good, poor, or otherwise.

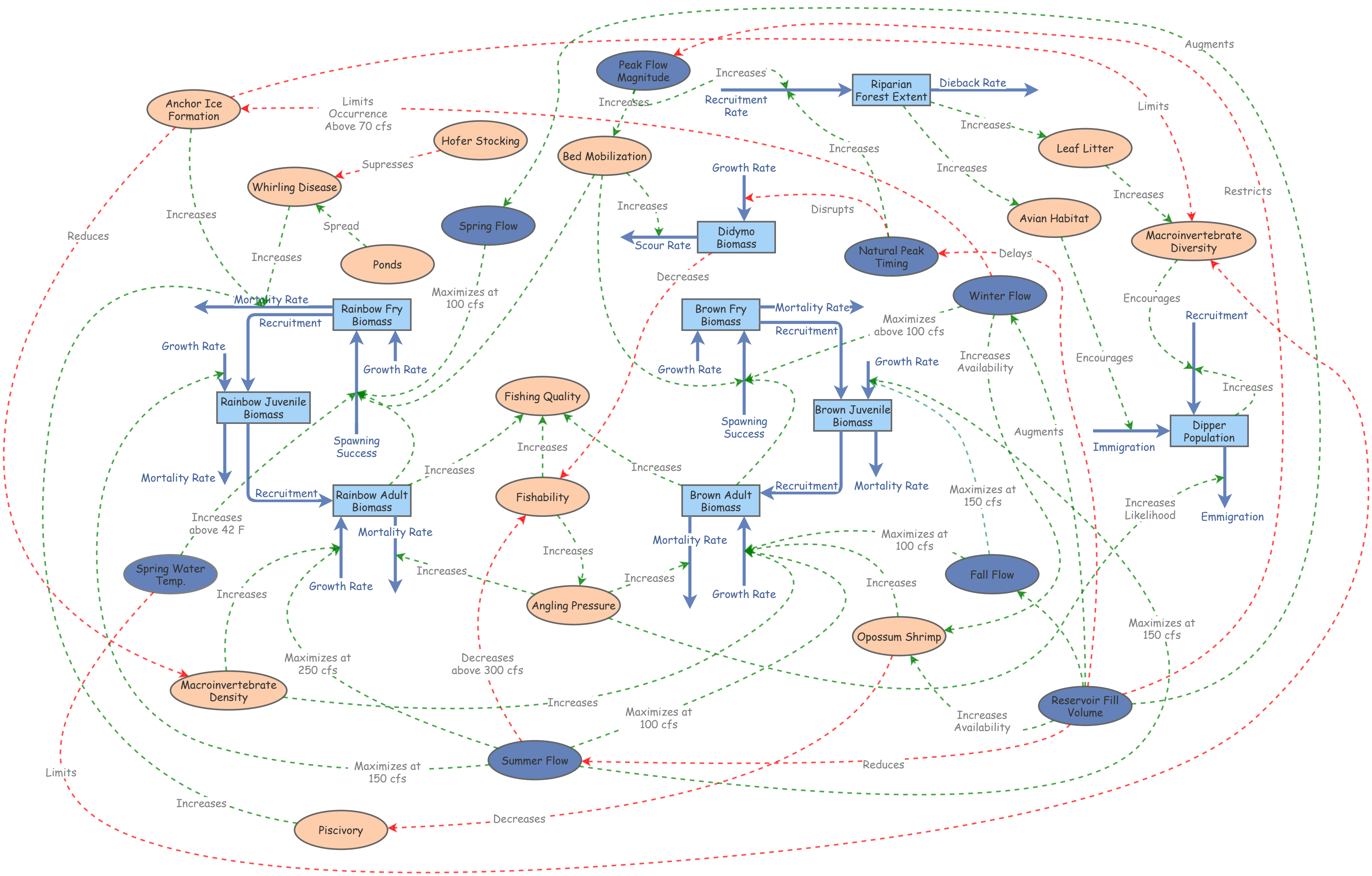


Figure 7. Conceptual model for the Fryingpan River linking ecosystem and hydrological variables and directional dependencies between them. Hydrological forcing variables indicated in blue ovals. Primary biological characteristics of interest represented as stocks and symbolized as blue boxes.

This conceptual model should be periodically reviewed with resource management agency personnel, consultants, researchers, and others to ensure that it reflects the current state of research and knowledge. These review sessions will provide a unique opportunity to collaboratively learn about the various interconnections represented in the model and explore the potential primary, secondary, and tertiary effects of some proposed streamflow management action. The conceptual model may also be useful in diagnosing the drivers of change in the system that push one ecosystem component in a favorable or unfavorable direction over time. For example, as didymo growth becomes more prolific and more of a management concern, greater time may be spent understanding the relationships between peak flows, bed sediment scouring, and growth rates and then exploring ways to optimize management of the system to achieve acceptable levels of didymo growth. Conversely, if changes in fish populations begin to degrade experiences for anglers, greater focus may be given to the parts of the system that moderate recruitment and growth rates for brown and rainbow trout.

It is important to note that this conceptual model does not instruct stakeholders in *how* to best manage conditions in the Fryingpan River. Rather, it intends to support reasoned decision-making in pursuit of some stated management goal or objectives that, themselves, may change over time. While the conceptual model cannot provide instruction or targets for management activities, the historical assessments completed on the Fryingpan River do provide some recommendations for streamflow management for the benefit of the ecosystem. The complexity of the conceptual model presented above should impress upon the reader that, while flow management may be a critical aspect of managing for specific ecosystem conditions, focusing only on streamflow without consideration of the other linkages and feedbacks present in the system will likely lead to some amount of confusion or dissatisfaction with management outcomes over the long term.

The conceptual model can be accessed and modified as needed at the following link: https://insightmaker.com/insight/203840/Riverine-Ecosystem-Model-for-the-Fryingpan-River.

3 Suite of Flow Recommendations for Ecosystem Maintenance

Healthy riverine ecosystems are maintained by a cycle of oscillating high spring and summer flows followed by low fall and winter flows. Native aquatic and riparian species have evolutionary adaptations built around this cyclical variability in streamflow. Thus, natural streamflow behavior should be approximated as closely as possible throughout a given year and between succeeding years to maintain the health of the native species in the Fryingpan River. Conversely, non-native sport fish benefit from an altered hydrological regime. Conclusions reached by previous investigators and a general desire for a pragmatic approach to flow management on the Fryingpan River supports binning hydrological behaviors into several periods deemed significant for the aquatic and riparian ecosystems. These periods include winter base flow, fall and spring spawning flows, and early summer peak flows. Each period features unique connections between hydrological behavior, aquatic macroinvertebrates, the fishery, and riparian vegetation.

The shape of the annual hydrograph became much more uniform following construction of Ruedi Reservoir. Annual peak flows are now truncated and fall flows are elevated so that far less variation exists in the hydrograph than would exist under unregulated conditions. Questions about the ecological ramifications of hydrological modification on the Fryingpan River resulted in numerous studies that attempted to identify "optimal" flow management targets for notable or emblematic species living in and along the river course. Flow recommendations provided below reflect recommendations made in these studies (Appendix A) or obtained through new analyses conducted as a part of this effort (Table 1). Future work on the Fryingpan River may lead to revision or disqualification of any of these recommended environmental flow thresholds.

Table 1: Target environmental flows for ecosystem maintenance, with associated sources and rationales.

Month	Minimum Flow Range		Optimum Flow Range		Rationale and References
	Flow (cfs)	Days Met	Flow (cfs)	Days Met	
Jan	45-70	31	70-100	> 25	Prevent anchor ice formation (Miller Ecological Consultants, 2006)
Feb	45-70	28	70-100	> 22	Prevent anchor ice formation (Miller Ecological Consultants, 2006)
Mar	45-70	31	70-100	> 25	Prevent anchor ice, rainbow spawning (Nehring, 1988b; Ptacek et al, 2003; Miller Ecological Consultants, 2006)
Apr	45-70	30	100-120	> 24	Rainbow spawning (Ptacek et al, 2003)
May	45-70	31	100-120	> 25	Rainbow spawning, start spring peak (Ptacek et al, 2003)
Jun	100-150	30	150-250	> 24	Rainbow trout habitat (Nehring, 1988b; Ptacek et al, 2003)
	400	> 15	530	> 10	Fine sediment flushing (Appendix B)
	700	> 5	1000	> 3	Didymo scour, bed load transport (CMC, 2015, Appendix B)
Jul	100-150	31	150-250	> 25	Rainbow trout habitat (Nehring, 1988b; Ptacek et al, 2003)
Aug	100-150	31	150-250	> 25	Rainbow juvenile habitat (Nehring, 1988b; Ptacek et al, 2003)
Sep	100-150	30	150-250	> 24	Brown trout juveniles (Nehring, 1988b; Ptacek et al, 2003)
Oct	45-70	31	100-150	> 25	Brown trout spawning (Ptacek et al, 2003)
Nov	45-70	30	70-100	> 24	Prevent anchor ice formation (Miller Ecological Consultants, 2006)
Dec	45-70	31	70-100	> 25	Prevent anchor ice formation (Miller Ecological Consultants, 2006)

3.1 Winter Flows

Previous research indicates that winter flows should be low enough to preserve incubating brown trout eggs, but high enough to prevent anchor ice formation. Absolute minimum instream flows of 47.5-65 cfs were the original recommendations produced by modeling studies for the winter period (Nehring 1979). Subsequent studies by fish biologists recommend a minimum flow of 65 cfs for brown trout egg incubation during the winter, with an optimal flow of 100 cfs (Nehring 1988b). These low flows should last from approximately November until March. Notably, pre-dam winter flows on the Fryingpan averaged 39 cfs (Simons, Li, and Associates 1983) over this same period. While little data on benthic macroinvertebrates and anchor ice exists for the pre-dam period, it is likely that dam regulation has enhanced winter conditions for brown trout and macroinvertebrates by decreasing anchor ice formation. Hoppe and Finnell (1970) stated that flows should not drop below 100 cfs during the winter unless necessary to prevent anchor ice formation. Recent research funded by the Roaring Fork Conservancy identified 70 cfs as the critical flow needed to prevent excessive anchor ice formation (Miller Ecological Consultants 2006). Although anchor ice could still form at and above this threshold, the study found that benthic macroinvertebrate survival rates increased significantly in winters where average flows were greater than 70 cfs.

3.2 Spring spawning flows

One of the key functions of spring flows is the triggering of rainbow trout spawning, which occurs from roughly the start of April through the middle of May. Previous studies determined that flows between 100 cfs (Nehring 1988b) to 120 cfs (Miller Ecological Consultants 2003) are ideal for the initial phases of the rainbow trout life cycle. Total spawning habitat is maximized at these flows, which is presumed to lead to reproductive success. However, rainbow trout reproductive success is likely temperature-limited on the Fryingpan River. Nehring & Anderson (1982) show that water temperatures lower than 42°F in the spring lead to thermal shock and can significantly reduce reproductive success for rainbow trout. These conditions occur regularly on the river below Ruedi Reservoir. Unnaturally cold outflows from Ruedi Reservoir in the spring also delay hatching as eggs do not reach the accumulated temperature that triggers emergence (Miller Ecological Consultants 2003). There is no evident management alternative for alleviating the negative impacts of cold water temperatures on rainbow trout spawning success.

3.3 Summer peak flows

Annual high peak flows from snowmelt serve critical ecosystem functions including nutrient distribution, sediment transport, and channel maintenance. Unregulated high summer flows on the Fryingpan averaged 1,024 cfs but in the period after construction of Ruedi Reservoir peak flows averaged 296 cfs (Simons, Li, and Associates 1983). USGS gage records show that peak flows have declined, especially since the last renegotiation of the water marketing program in 1989. Truncation of peak flows may result in deleterious ecosystem impacts, including loss of habitat complexity and channelization of the river corridor. Reduced peak flows increase the occurrence of didymo blooms in the summer due to reduced sediment mobilization and a concentration of nutrients in the stream channel (CMC RMP 2014; CMC RMP 2015).

A pair of studies by Colorado Mountain College observed that periods where peak flow persists above 700 cfs for multiple days leads to reduced didymo cover and abundance (CMC RMP 2014; 2015). This can be attributed to the scouring effect of bedload transport and a redistribution of nutrients outside of the main channel to overbank areas. Bedload transport modeling (Appendix B) suggests that 700 cfs triggers mobility of all sediment sizes at most sites along the Fryingpan River. Flows of 530 cfs mobilize flush sand-sized and finer particles (< 5.6 mm) from the streambed in most river reaches (Table 1). However, higher flows are much more efficient at transporting sediment. Flows of ~1,000 cfs conduct more geomorphic work and better approximate the discharge of the pre-dam hydrologic regime. While these flow targets may seem high, flood frequency analysis shows that even after the construction of Ruedi Reservoir, flows of 700 cfs have a 2-year recurrence interval, while flows of 1,000 cfs have roughly a 4-year recurrence interval.

The timing of peak flow is also important. Aquatic species in the Fryingpan River are adapted to a snowmelt-dominated flow regime where the peak almost always occurs between late May and early July. Since the management strategy of Ruedi Reservoir was changed in 1989 to help increase flows for endangered species in the Colorado River near Grand Junction, peak flows on the Fryingpan River occurred in the fall period (Sept.-Nov.) nine out of 30 years. In the prior 25 years, the annual peak only occurred in the fall period only once. Shifting the timing of the annual peak flow from early summer to fall may interfere with the lifecycle and patterns of behavior of numerous riverine species, particularly native species adapted to snowmelt runoff regimes. Peak flows that occur between May and July are, thus, expected to be most beneficial to native species.

3.4 Fall spawning flows

Before flow regulation, fall on the Fryingpan River was characterized by waning streamflows and cooling waters. However, the annual peak now often occurs in the fall, and water temperatures reach their peak due to turning over of water in Ruedi Reservoir (Miller Ecological Consultants 2003). Brown trout spawning occurs in the fall roughly from mid-October to mid-November (Nehring 1988b). Early studies recommended streamflows of 100 cfs to protect brown trout eggs after the water temperature drops to 48°F or on October 15, whichever comes first (Hoppe & Finnell 1970). Instream flow modeling found ideal rainbow trout juvenile habitat is maximized in the fall at 150 cfs and brown trout spawning and incubation habitat area is maximized at 100 cfs during this same period (Nehring 1988b).

4 Development of Ecological Decision Support Systems

RFC requires tools to help understand the ecological impacts of different reservoir release strategies from Ruedi Reservoir. Two tools were developed here. The first tool predicts the probability of an exceedance of water temperature water quality standards on the Roaring Fork River in Glenwood as a function of air temperature, streamflows on the Roaring Fork, and the flow contributions from Ruedi Reservoir. The second tool predicts ecologically-relevant hydrological regime characteristics using streamflow and climate forecasting data for the Colorado River Basin. Both tools were developed as Bayesian network models and intend to provide decision makers and stakeholders with a means for characterizing events of interest in probabilistic terms, exploring the effects of forecast uncertainty on predictions for the future.

Bayesian network models are probabilistic models that represent variables and the conditional dependencies between them as a directed acrylic graph. The visual structure of these models and the definition of relationships between variables with conditional probability tables makes them a useful choice for RFC in this setting. Bayesian network models are also well suited to applications where the uncertainty in the relationships between variables is high and where those relationships are described in both qualitative and quantitative terms. The models can be useful for both 1) predicting the likelihood of certain events given a set of inputs and 2) exploring and dialoguing about the structure of the model itself in a guided participatory process. It is our hope that each of these tools will be useful to local water management and decision making in the years to come. Each tool is described in detail below.

4.1 Bayesian Network Model for Predicting Water Temperature Exceedances

Roaring Fork Conservancy and other stakeholders require a tool that can evaluate the effectiveness of various Ruedi Reservoir release strategies for mitigating high water temperatures harmful to trout and other aquatic life on the Roaring Fork River under observed or predicted meteorological conditions. In response, a Bayesian network model was developed for predicting the probability of exceeding State of Colorado water quality standards for water temperature on the Roaring Fork River in Glenwood Springs. The structure of this model is fairly simple and, thus, provides a useful introduction to the methods selected for development Bayesian network models, the basic form of the model outputs, and the practical applications of these models as decision support tools.

Relationships between streamflow, atmospheric and solar conditions, and water temperature are well established in the scientific literature. Various approaches are used to evaluate the impact of increasing or decreasing streamflow on water temperature. Some methods rely on solving detailed energy balance equations, while others develop simple predictive models using linear regression. A full discussion of the variety of approaches used elsewhere is not warranted here but Benyahya et al. (2007) and Caissie (2006) provide reviews of the most common deterministic and stochastic modeling practices. The structure of nearly all stream water temperature models reflects a conceptualization of the physics that govern water temperature regimes. Incoming shortwave radiation from the sun and longwave radiation emitted from clouds, hillslopes, and the streambed transfer energy to the water column. Increasing streamflows adds thermal inertia to the system, requiring more radiation per unit area of exposed water surface to achieve a specific degree of warming. Air temperature is regularly used as a proxy for incoming shortwave and longwave radiation. Air temperature measurements are easy to obtain and good historical records are available in most locations, greatly simplifying calibration and validation of predictive models.

The Bayesian network model described here is a form of stochastic stream temperature model, not dissimilar from linear regression models described elsewhere in the scientific literature. The specific conceptual model used here is detailed as a Directed Acrylic Graph (DAG) where system variables are described as nodes and the directional dependencies between them are described as links (Figure 8). The model structure dictates that the Maximum Weekly Average Water Temperature (tempGWS_MWAT) calculated on the Roaring Fork River at Glenwood Springs for the seven day period leading up to an observation day is controlled by the weekly average air temperature (airWAT) computed for the seven day period leading up to the observation day, the log-transformed observed streamflow in the Roaring Fork River on the observation day (GlenwoodQ) and the fraction of that water supplied by Ruedi Reservoir releases (RuediFraction). The model was structured as simply as possible using readily available observational data. This same data is regularly produced in forecasting products by the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service (NWS), and others.

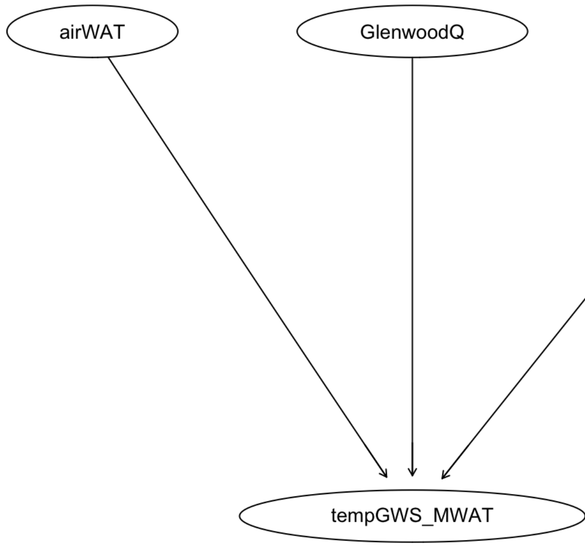


Figure 8. Directed Acrylic Graph indicating conceptual relationships between Maximum Weekly Average Water Temperature of the Roaring Fork at Glenwood Springs (tempGWS_MWAT) and the system variables expected to predict variability and water temperature, including: weekly average air temperature (airWAT), streamflow in the Roaring Fork River (GlenwoodQ) and the fraction of that flow coming from Ruedi Reservoir (RuediFraction).

Long term U.S. Geological Survey (USGS) streamflow records for the Fryingpan River below Ruedi Reservoir (USGS 09080400) and the Roaring Fork River in Glenwood Springs (USGS 09085000) were retrieved from the National Water Information System (NWIS) for the 2013-2020 period. Daily air temperature data for the same period was retrieved for the GLENWOOD SPGS #2 meteorological station from Colorado Climate Center at Colorado State University (https://climate.colostate.edu/data_access.html). All data was processed in the *R* statistical computing environment (https://cran.r-project.org). The Bayesian network model was constructed using the *bnlearn* library and the model structure was defined a-priori. Tests conducted on the fitted model indicate that air temperature more strongly controls water temperature than streamflow or release fractions from Ruedi (Table 2). However, all effects are present so the streamflow variables are included in the model.

The constructed model uses historical streamflow and meteorological observations to compute the probability of an event given some set of future streamflow and air temperature values. Uncertainty in the values associated with those future conditions can be represented in the model as ranges. For example, the probability of observing an MWAT in the Roaring Fork River at Glenwood Springs greater than or equal to 18.3° C is 73% when streamflows at Glenwood are predicted to be between 500-550 cfs, weekly average air temperatures are predicted between 24-25° C, and Ruedi Reservoir release fractions are expected to be between 26 -30% of the total streamflow at Glenwood. The model can thus be used to explore the impact of various reservoir release scenarios on water temperature given a set of predictions about meteorological and hydrological conditions in the immediate future.

Table 2. Bayesian network parameters for the fitted network model.

```
Bayesian network parameters

  Parameters of node airWAT (Gaussian distribution)

Conditional density: airWAT
Coefficients:
(Intercept)
   20.26708
Standard deviation of the residuals: 2.824861

  Parameters of node GlenwoodQ (Gaussian distribution)

Conditional density: GlenwoodQ
Coefficients:
(Intercept)
   7.007085
Standard deviation of the residuals: 0.6386299

  Parameters of node ReudiFraction (Gaussian distribution)

Conditional density: ReudiFraction
Coefficients:
(Intercept)
  0.2630617
Standard deviation of the residuals: 0.1350586

  Parameters of node tempGWS_MWAT (Gaussian distribution)

Conditional density: tempGWS_MWAT | airMax + airWAT + GlenwoodQ +
ReudiFraction
Coefficients:
  (Intercept)        airWAT      GlenwoodQ  ReudiFraction
  34.2302238      0.3008526     -3.3541257     -6.8139100
Standard deviation of the residuals: 0.592982
```

The fitted model is encoded into a Shiny web application (https://shiny.rstudio.com) and made available for use by RFC and other stakeholders involved in Fryingpan River flow management decision making. The application enables users to enter ranges of values (as described above) for anticipated streamflow, reservoir releases, and air temperatures for some period in the future—likely, the coming week—when forecast data is available. This set of information is the "evidence" for the model. The user is required to describe a water temperature threshold of interest. This threshold is the "event" for the model. For any set of entered values, the model will return the probability of the event, conditioned on the evidence, expressed as a percent chance between zero and one. The model asks users to characterize expected streamflow and temperature conditions as a range. This feature allows users to incorporate some degree of uncertainty into model results. The selected range of values determines the bounds of the uniform sampling distributions used by the software to make predictions. It is up to the user to determine the “best” range of expected values using weather forecast probabilities, reviews of historical data, conversations with local water managers, or other sources.

Use of the model in decision-making settings should help RFC and others understand how and when water deliveries from Ruedi Reservoir can be leveraged to meet environmental needs on the Roaring Fork River. A web application version of the model can be accessed by RFC and other stakeholders at: https://lotic.shinyapps.io/RoaringFork_WaterTemps/. The application can be embedded in an RFC website as an `<iframe>` HTML object.

4.2 Bayesian Network Model for Predicting Hydrological Regime Behavior

The primary goal of this effort is to produce a decision support tool for RFC that will help predict ecologically relevant hydrological regime behaviors on the Fryingpan River based on streamflow and climatological forecasting data. Specifically, RFC requires a tool that helps predict streamflow behavior relative to the environmental flow targets outlined previously (Table 1). Annual predictions of hydrological regime behavior during the upcoming year will support RFC’s efforts to engage in water management discussions with the Colorado River Water Conservation District, Colorado Water Conservation Board, City of Aspen, USBR, and others. A Bayesian network model was constructed to meet this need. An effort was made to develop a parsimonious model—one without an overabundance of input/output variables of dependency structures—to simplify its parameterization during the forecasting season and it use in decision-making settings. Nonetheless, the resultant DAG is more complex than that described in the previous section (Figure 7) and may require some review by relevant stakeholders.

The model was constructed using the *bnlearn* library in *R*. The model structure was defined manually and the Bayesian network was trained using historical data for each of the variables (Table 3) collected over the 1990-2013 period. This period of record was selected because it reflects the expected present-day operations of Ruedi Reservoir without the influence of recent water purchases by CWCB—the model, thus, predicts contemporary flow behaviors in the absence of such actions. The fitted model structure is plotted as a DAG (Figure 9).

The fitted model provides probabilities of the various states of ecologically-relevant hydrological regime behavior variables, given a set of streamflow and climatological forecast values. For example, the implementation of the model allows the user to evaluate the probability of annual or May-July peak flows lower than a selected threshold (e.g. 700 cfs), given a set of forecast values for Colorado Basin April-September PHDI values, Colorado Basin May 1st SWE totals, April-July streamflow yields on the Colorado River at Cameo and Dotsero, and April-July streamflow yields on the Roaring Fork River at Glenwood Springs. All streamflow yield values are converted to anomalies and log-transformed by the software. Values are input as ranges that reflect the uncertainty in the prediction for any given variable.

Input streamflow forecast values and estimates of SWE and projected PHDI can be readily retrieved from forecasting publications produced monthly by NRCS. The Water Supply Outlook Reports for the Colorado River Basin are an excellent source of existing condition and forecast data for snowpack and streamflows. These reports can be retrieved at the following location: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/co/snow/waterproducts/basin/.

Table 3. Bayesian network variable descriptions.

Variable	Description	Statistic	Period	log Transformed
AMJJAS_PHDI	Palmer Hydrological Drought Index (PHDI) values for the Colorado, Climate Division 2. Positive PHDI values indicate the hydrological impacts of drought where more negative values indicate increasingly severe impacts.	Median	May-July	FALSE
May1_SWE	Colorado Basin Snow Water Equivalent (SWE) as of May 1st. Values are median total SWE calculated from SNOTEL sites across the Colorado River Basin with the most recent 1981 to 2010 normals period.	Total	Prior to May 1st	FALSE
CameoAnomoly	Departure of the total April-July streamflow (KAF) volume for the Colorado River at Cameo from the 1990-2013 median.	Total	April-July	TRUE
GlenwoodAnomoly	Departure of the total April-July streamflow (KAF) volume for the Roaring Fork River at Glenwood Springs from the 1990-2013 median	Total	April-July	TRUE
DotseroAnomoly	Departure of the total April-July streamflow (KAF) volume for the Colorado River at Dotsero from the 1990-2013 median	Total	April-July	TRUE
minJan_Anomoly	Departure of January minimum streamflow (cfs) from the median winter (Jan-Mar) streamflow for the 1990-2013 period.	Minimum	January	TRUE
minFeb_Anomoly	Departure of February minimum streamflow (cfs) from the median winter (Jan-Mar) streamflow for the 1990-2013 period.	Minimum	February	TRUE
minMar_Anomoly	Departure of March minimum streamflow (cfs) from the median winter (Jan-Mar) streamflow for the 1990-2013 period.	Minimum	March	TRUE
MJJ_PeakAnomoly	Departure of the May-July peak flow magnitude (cfs) from the median annual peak flow for the 1990-2013 period	Maximum	May-July	FALSE
peakAnomoly	Departure of the annual peak flow magnitude (cfs) from the median annual peak flow for the 1990-2013 period	Maximum	October-September	TRUE
SON_Anomoly	Departure of the median September-November flow (cfs) from the median flow for that same season across the 1990-2013 period	Median	September-November	TRUE

The model requires as input, a characterization of forecast streamflow conditions as a range. This feature allows users to incorporate some degree of uncertainty into model results. The selected range of values determines the bounds of the uniform sampling distributions used by the software to make predictions. It is up to the user to determine the "best" range of expected values to enter based on presentations of likelihoods/percentiles in the Water Supply Outlook Reports, local knowledge, or conversations with experts (Figure 10, Figure 11).

A web application version of the model can be accessed by RFC and other stakeholders at: https://lotic.shinyapps.io/Fryingpan_Flow_Predictions/. The application can be embedded in an RFC website as an `<iframe>` HTML object.

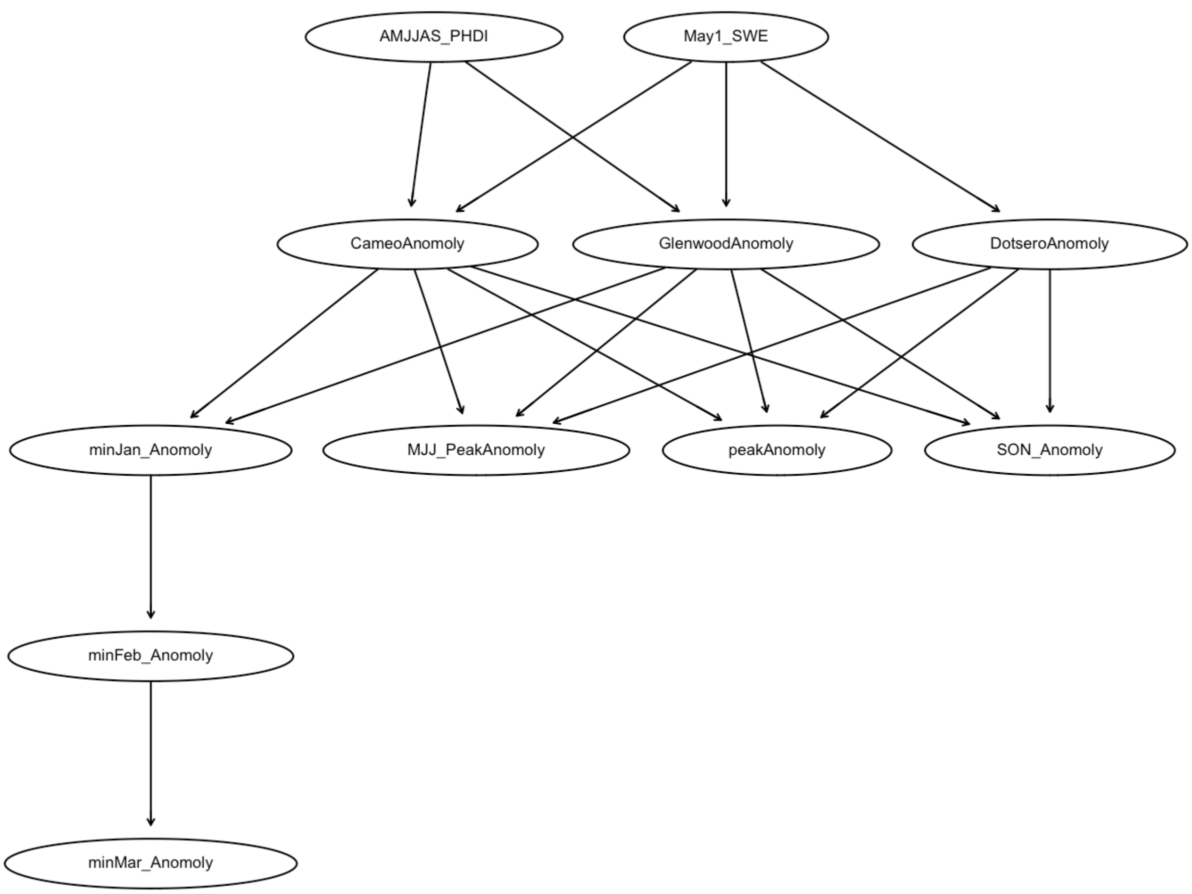


Figure 9. DAG for the Bayesian network model used to predict streamflow behavior on the Fryingpan River with streamflow and climatological data for the Colorado River basin.

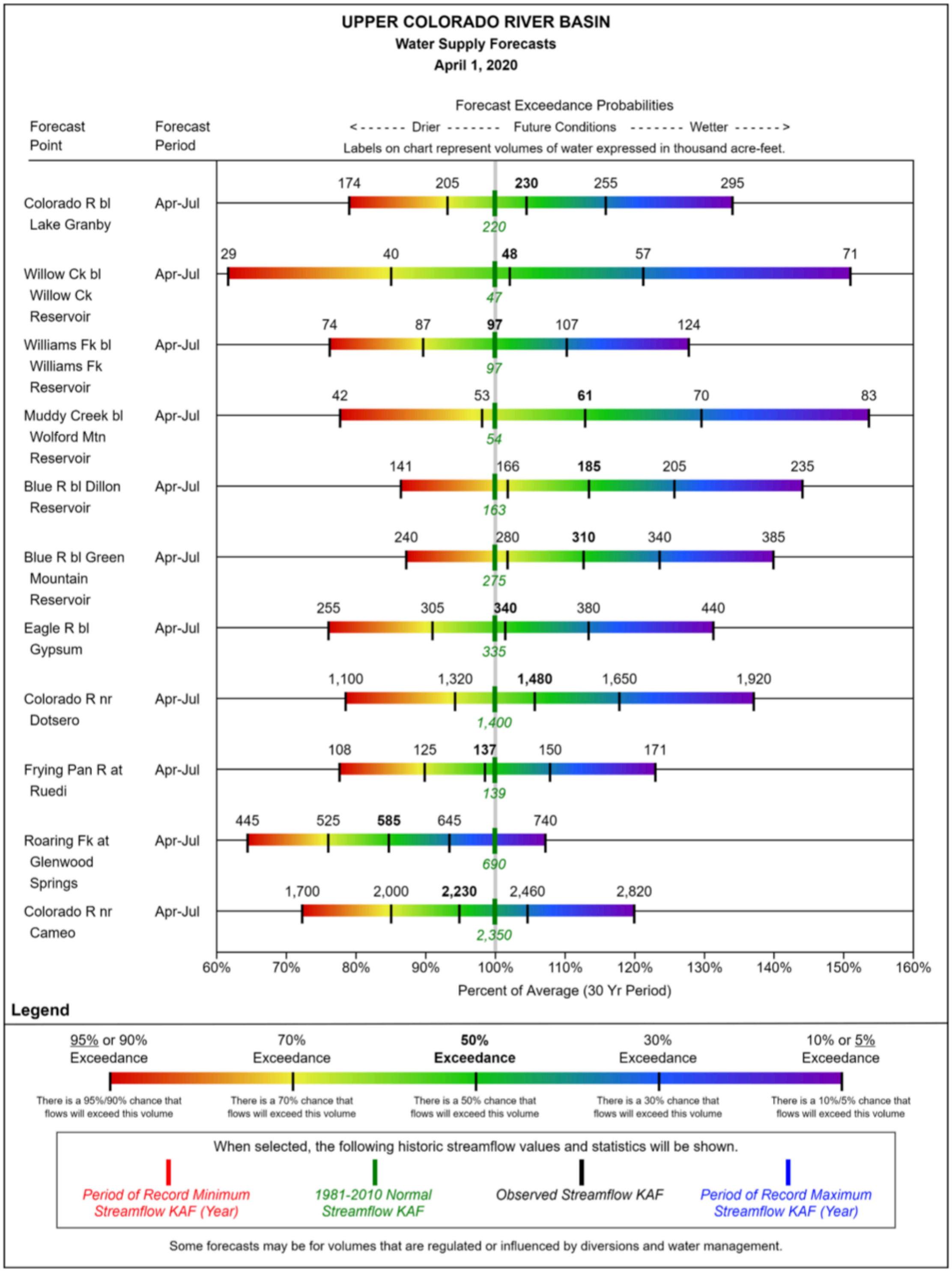
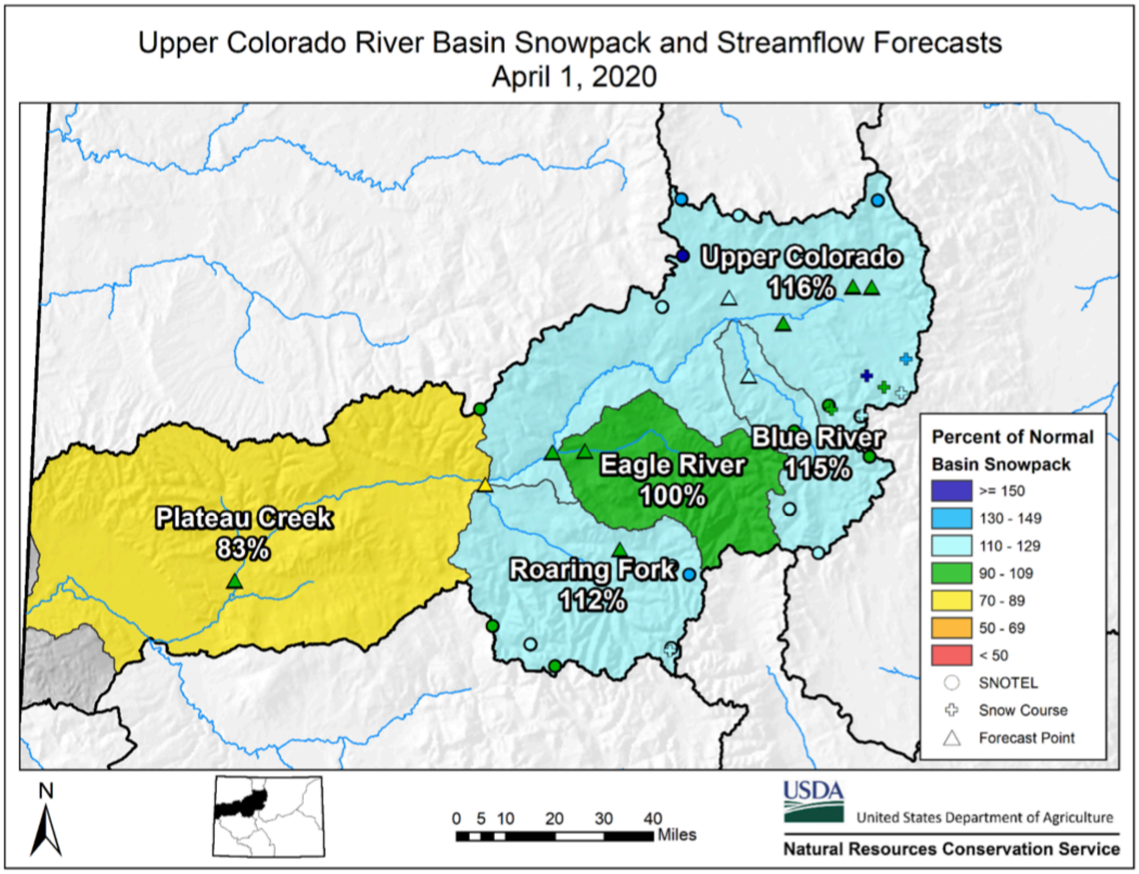


Figure 10. Example graphic from the April 1st, 2020 Water Supply Outlook Report indicating the range of probable AMJJ streamflows for selected stream gauge locations across the Colorado River basin. Users of the Fryingpan streamflow prediction web app may choose to use the 70% and 30% exceedance bounds or some other points as the basis for the entered ranges of predicted streamflow.



Watershed Snowpack Analysis April 1st, 2020

Sub-Basin	# of Sites	% Median	Last Year % Median
Blue River	5	115	137
Upper Colorado	25	116	121
Muddy Creek	3	133	130
Eagle River	4	100	119
Plateau Creek	5	83	136
Roaring Fork	8	112	147
Williams Fork	5	112	114
Willow Creek	2	121	132
Basin-Wide Total	35	113	129

*SWE values calculated using first of month SNOTEL data and snow course measurements

Figure 11. Example graphic from the April 1st, 2020 Water Supply Outlook Report indicating SWE as a percent of average for watersheds across the Colorado River basin. Users of the Fryingpan streamflow prediction web app may choose to use the reported SWE percentage plus or minus some amount (e.g. 10%) as the basis for the values entered into the web app.

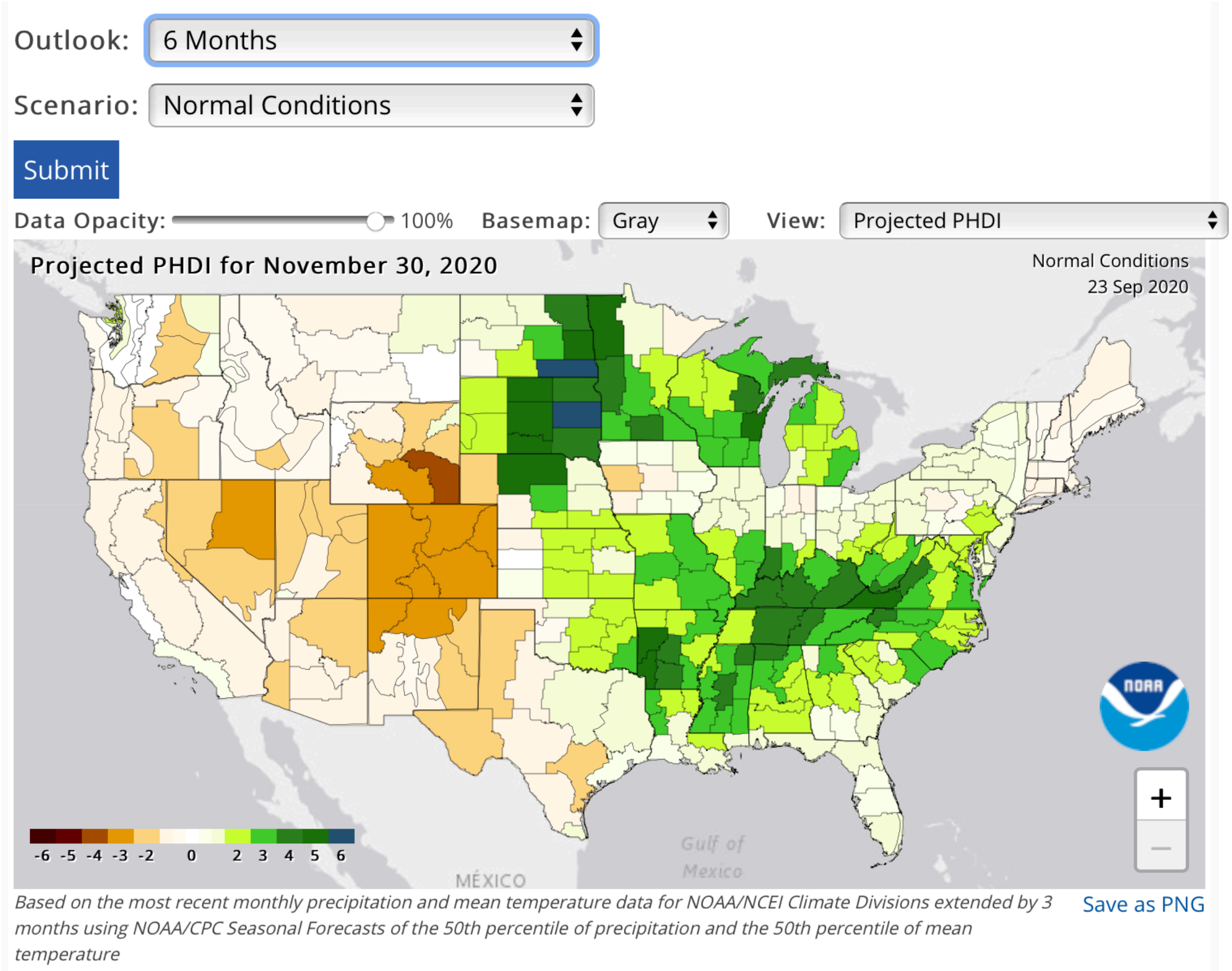


Figure 12. Example graphic from the Projected Palmer Hydrological Drought Index mapping application provided by NOAA. Users of the Fryingpan streamflow prediction web app may choose to use the "Hot and Dry" and "Cold and Wet" scenario values for the western Colorado region to inform the selection of the PHDI range entered into the web app.

5 Next Steps

The concepts, information, and tools presented in the preceding sections will be most useful to RFC and other local stakeholders where they are incorporated into an adaptive management framework. Adaptive management is simply a management approach that responds to new data and information over time as it relates to success or failure at meeting some stated set of goals or objectives. Several examples of successful adaptive management of water resources are available in Colorado. Most notably, the Learning By Doing effort in Grand County is monitoring ecosystem conditions following expansion of two large transmountain diversion projects. Annual data collection and analysis efforts yield information about changing conditions, which can be addressed with on-the-ground action or expanded monitoring and analysis to better understand a given issue. Some suggestions for structuring an adaptive management process on the Fryingpan River are provided here.

Any functional adaptive management process is built on functional personal and professional relationships. Recent dialog between Roaring Fork Conservancy, the Ruedi Water and Power Authority, City of Aspen, Colorado Water Conservation Board, Colorado River Water Conservation District, and the Bureau of Reclamation resulted in a commitment from all parties to participate in ongoing cooperative dialog about optimization of water releases to support multiple uses. RFC will need to work with these partners to formalize schedules and timelines for dialog, data review, and water management decision-making. One such example structure is provided here as a straw man (Figure 13).

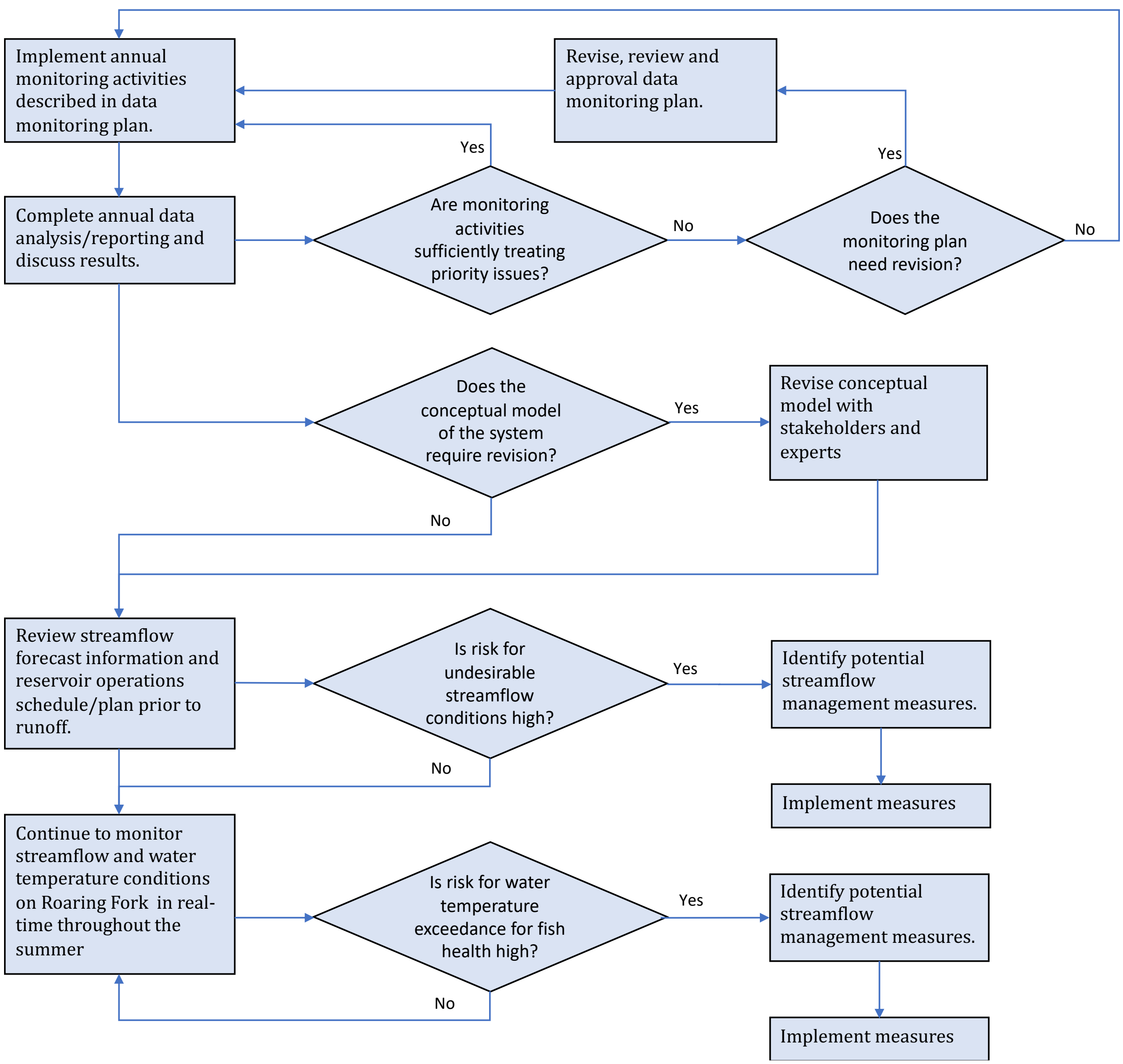


Figure 13. Potential adaptive management framework for water management decision-making on the Fryingpan River.

The basic components of any adaptive management plan should include:

- annual data collection and analysis plan that is reviewed and modified, as needed, on a regular schedule;
- periodic review and revision, if needed, of the conceptual model of ecosystem structure and behavior;
- annual dialog with all stakeholders about current environmental management priorities (e.g. spawning habitat for brown trout, didymo, etc.);
- annual review of streamflow predictions for the Fryingpan River in the spring (April or May) of each year and an assessment of the risk of not meeting selected management targets;
- identification and implementation of water management actions to reduce risk to one or more components of the riverine ecosystem;
- weekly or bi-weekly monitoring of water temperatures in the Roaring Fork River at Glenwood Springs followed by evaluations of risk for exceeding water quality standards throughout the July-September period; and
- identification and implementation of management actions to reduce risk of exceeding water temperature thresholds.

The information and tools presented here are directly relevant to many of the bullets above. In fact, they were made for use in an adaptive management setting. As new information becomes available, existing models/tools become obsolete, or the focus of the stakeholders shifts to different environmental, recreational, hydropower or consumptive water use needs, some revision of this document may be required.

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Appendix A: Annotated Bibliography

Annotated Bibliography

Preface

A large number of historical studies and reports examine the impact of Ruedi Reservoir on these aquatic resources. Twenty-three of these reports and investigations are summarized below. Notably, a literature review conducted by Miller Ecological Consultants in 2002 provides similar information and covers many of the same reports. This annotated bibliography includes reports completed after 2002 and focuses on studies that provide information on environmental flows and temperature regimes and how they impact various aspects of the riverine ecosystem. Studies are listed in order of their publication date. A more complete set of reference documents and descriptions is delivered along with this document as a Zotero (Zotero.org) collection called Zotero_Fryingpan_Collection.rdf. This collection includes reference/publication information, short descriptions, and embedded documents for each citation.

1. **Hunter G.N., and O.A. Parson. 1943. A Stream Census of the Fryingpan River, 1942-1943. Colorado Game and Fish Department.**

This study provided the first characterization of the Fryingpan River and its fishery. At that time, the Fryingpan River was an unregulated snowmelt-fed pool-riffle stream with an average gradient of 86 feet per mile and open river banks. Fish species included rainbow trout, cutthroat trout, brown trout, eastern brook trout, and sculpin. The stream was found to have large amounts of aquatic macroinvertebrates and numerous areas for cover for fish such as cut-banks, tree roots, logjams, and low velocity reaches. Water temperature ranged from 47-62F, diatoms and algae were found throughout the stream, and stream widths averaged 65 feet. While not surveyed, several tributaries were thought to contain favorable habitat.

2. **Hoppe, R.A. and L.M. Finnell. 1970. Aquatic Studies on Fryingpan River, Colorado – 1969-1970. Colorado Division of Wildlife. Fort Collins, Colorado.**

This study focused on options for improving rainbow and brown trout spawning outcomes in the Fryingpan River. Field studies in the winter of 1969-70 included surveys of spawning redds, electrofishing, and temperature measurements. In order to protect brown trout eggs the study recommended that after the water temperature drops to 48F or on October 15, whichever comes first, the discharge should be set to 100 cfs at least until November 15. This study also recommended that flows should not drop beneath 100 cfs unless absolutely necessary to minimize downstream icing.

3. **Finnell, L. M. and G. L. Bennet. 1977. Fryingpan-Arkansas Fish Research Investigations. Colorado Division of Wildlife. Final Report.**

This study sought to determine what influence Ruedi Reservoir had on the Fryingpan River below the dam. Water in the Fryingpan River was found to have higher pH, hardness, and conductivity than water upstream of the reservoir, which the authors attributed to gypsum deposits that had been submerged by the reservoir. The temperature regime of the river was also found to be altered, with the average summer water temperature dropping from 14.5C to 8.1C after dam construction. The authors also observed an increase in growth of algal mats below the dam. However, rainbow trout growth rates appeared normal and brown trout growth rates appeared above average. The authors could not conclude if the dam had negative or positive effects on the ecosystem downstream of Ruedi Reservoir.

4. **Nehring, R. B. 1979. Evaluation of instream flow methods and determination of water quality needs for streams in the State of Colorado. Colorado Division of Wildlife. Fort Collins, Colorado.**

The focus of this study was a comparison of four methods used to evaluate instream flows, including Single and Multiple R2Cross, IFG4, and the "Montana Method". The Fryingpan River was one of many streams evaluated in the study, and it was determined that all methods besides the "Montana Method" produced similar and reliable results. Minimum flows for the Fryingpan River based on this study ranged between 47.5 and 65 cfs depending on which method was used.

5. **Nehring, R. B. and R. Anderson. 1982. Stream Fisheries Investigations Job Progress Report. Colorado Division of Wildlife. Federal Aid in Fish and Wildlife Restoration Project F-51-R-7. Fort Collins, Colorado.**

This study compared fishing success and fish population data from 1981 with data gathered in previous years. The data showed that large trout in particular and the trout population in general were declining in reaches of the Fryingpan with 8 trout per day bag limits. Rainbow trout populations were declining in the catch-and-release section of the Fryingpan due to reproduction challenges. The authors said that frequently low temperatures (below 42F) could lead to large losses in rainbow trout eggs due to thermal shock. Bag limits of one rainbow trout and one brown trout per day were recommended.

6. **Simons, Li and Associates Inc. 1983. Fryingpan-Arkansas Project, Ruedi Resevoir, Colorado, Round 2 Water Sale, Environmental Assessment. Prepared for Bureau of Reclamation. Denver, Colorado.**

The purpose of this study was to compare the environmental consequences of various management strategies controlling water sales from Ruedi Reservoir. This study evaluated: the relative impacts of each alternative on threatened endangered species, physical and chemical effects on fisheries in downstream water bodies, potential scouring and erosion, recreation usage, winter water sales to preserve a high summer water level, salinity increases in the Colorado River, and others.

A summary of aquatic resources on the Fryingpan River found Colorado River cutthroat trout, rainbow trout, brown trout, brook trout, and mountain whitefish to be present. Average winter flows before Ruedi Reservoir were 39 cfs while regulated average winter flows were 111 cfs. Average unregulated summer peak flows were 1024 cfs while regulated peak flows averaged 296 cfs. Key areas containing spawning gravels were focused around Seven Castles Creek, Taylor Creek, and just beneath the dam outlet. In general, the macroinvertebrate community was found to be typical of high-quality streams yet longitudinal variation was observed, with chironomids dominating just below the dam and caddisflys dominating with distance from the dam, possibly due to increasing fine particulate matter downstream. The main threatened species in the Fryingpan, the Colorado River cutthroat trout, was reported to inhabit a two-mile section but had not been able to spawn.

7. Nehring, R. B. and R. M. Anderson. 1984. Stream Fisheries Investigations. Colorado Division of Wildlife. Federal Aid Study F-51. Fort Collins, Colorado.

This study evaluated the impacts of the bag limits imposed on the Fryingpan River in response to declining rainbow trout populations in 1981. Low reproductive success due to cold releases from Ruedi Reservoir had led to stricter take limits and stocking of rainbow trout fingerlings in 1981/82. These stocked fish were found to be surviving, growing, and competing with brown trout.

8. Nehring, R. B. 1988a. Stream Fisheries Investigations. Colorado Division of Wildlife. Federal Aid Project F-51-R. Fort Collins, Colorado.

The intent of this study was to find correlations between water releases and fish success. The study found no significant correlations between flows and fish success due to a variety of factors including: stocking of rainbow trout fingerlings, changes in management regulations and bag limits, a 30% increase in fishing pressure, and the introduction of mysis shrimp during retrofitting of the hydropower generator in 1985.

9. Nehring, R. B. 1988b. Stream Fisheries Investigations. Colorado Division of Wildlife. Federal Aid Project F-51-R. Fort Collins, Colorado.

This study used PHABSIM and instream flow incremental methodology (IFIM) modeling to determine the optimum and minimum flows for every time period and life stage for rainbow trout and brown trout in the Fryingpan River. Minimum flows year-round ranged from 50-65 cfs and optimal flows ranged from 100-250 cfs. 100 cfs was determined to be the optimum flow for all life stages of brown trout and the spawning, incubation, hatching, and fry rainbow trout life stages. Flows of 150 cfs for juvenile rainbow trout and 250 cfs for adults were found to be optimal.

10. U.S. Department of Interior, Bureau of Reclamation, Simons, Li and Associates Inc., Environmental Research and Technology, Inc. 1989. "Ruedi Reservoir, Colorado, Round II Water Marketing Program, Final Supplement to the Environmental Statement, Fryingpan Arkansas Project. Denver, Colorado.

This study compared the environmental impacts of three alternatives for water delivery from Ruedi Reservoir; a No Action Alternative, a Preferred Alternative, and a Preferred Alternative with Conservation Measures. Flows on the lower Fryingpan River were expected to decrease in wet years and increase in dry years compared to the No Action Alternative. The report used existing data to evaluate the impacts on fish species, benthic macroinvertebrates, and habitat. The negative impacts of changing the flow regime included: habitat loss for trout, loss of cover for adult fish, loss of incubating trout eggs, and a decrease in benthic macroinvertebrate production.

The Preferred Alternative with Conservation Measures was not predicted to adversely impact rainbow or brown trout fry and juveniles. Planned flow reductions between November and April were predicted to negatively affect benthic macroinvertebrates and periphyton.

11. U.S. Department of Interior, Bureau of Reclamation. 1990. Ruedi Reservoir , Fryingpan-Arkansas Project, Final Supplement to the Environmental Statement, Round II Water Marketing Program, Record of Decision. Denver, Colorado.

This document states the decision by the Bureau of Reclamation to proceed with the Preferred Alternative with Conservation Measures.

12. BRW, Dames and Moore, and Colorado State University. 1999. Roaring Fork and Fryingpan Rivers Multi-Objective Planning Project. Prepared for Colorado Water Conservancy Board.

This study was commissioned to create an integrated management plan in response to flooding on the Roaring Fork and Fryingpan Rivers. The main goals were to mitigate flood losses and improve irrigation supply for downstream users. The study noted that extensive human impacts have degraded the stream banks, encroached on riparian zones, and channelized the river through the construction of roads, levees, and homes. In addition to the physical modification of the riparian corridor, several instances of excessive sedimentation were documented to occur from development projects. This report highlighted the potential of Seven Castles Creek to contribute large amounts of suspended sediment to the system and impact aquatic resources.

13. Miller Ecological Consutants. 2002. Fryingpan-Roaring Fork Literature Review. Prepared for the Roaring Fork Conservancy.

This literature review was conducted as the first part of the Fryingpan Roaring Fork Fisheries Study. This study assembles 31 references pertaining to the fisheries and aquatic life of the Fryingpan and the Roaring Fork below Basalt. The information compiled here was used as historical information for the final fisheries report.

14. Miller Ecological Consultants. 2003. A Study of the Ecological Processes on the Fryingpan and Roaring Fork Rivers Related to Operation of Ruedi Reservoir. Prepared for the Roaring Fork Conservancy.

This study combined historical data with field studies and IFIM modeling to assess the health of the Fryingpan River and determine the impact of Ruedi Reservoir on the riverine ecosystem. Components of the study included: instream habitat and flow relationships, thermal regime of reservoir releases, a characterization of spawning habitat, and evaluations of benthic macroinvertebrate and fish populations.

The study found that the pre-dam hydrological regime was typical of a snowmelt-dominated mountain river, but winter flows increased and summer flows decreased after construction of Ruedi Reservoir. After Ruedi Reservoir's management strategy was changed in 1989 to help downstream endangered fish species, peak flows occurred during the late summer and early fall.

Water temperatures were found to be warmer in the winter and cooler in the summer as a result of impoundment, with impacts diminishing with distance from the dam outlet. The warmest temperatures occur in the late fall during reservoir turnover, while in a natural system water temperature would peak in late summer. Observed high water temperatures in the fall are suitable for brown trout spawning but low water temperatures in the spring have deleterious effects on rainbow trout spawning success. Sediment sampling shows that clean substrate is adequate for the emergence of fish, barring significant inputs of fine sediment.

IFIM modeling shows similar results to Nehring (1988b). Optimal flows for adult rainbow trout were approximately 250 cfs in low gradient reaches and 200 cfs in high-gradient reaches. Juvenile brown trout habitat peaks at 150 cfs, while spawning habitat for both species peaks at 100 cfs.

Fish population trends indicate that the Fryingpan River has shifted from being rainbow trout-dominated in the 1970s and 1980s to being brown trout-dominated today. Reasons of this shift could include a lack of stocking of rainbow trout in the 1990s and impacts from whirling disease. The study found brook trout and Colorado River cutthroat trout to be either extirpated from the system or rare.

Macroinvertebrate diversity is low immediately below Ruedi Reservoir but increases with distance downstream. It is believed that fewer species are able to survive the environment created by dam operation. Macroinvertebrate densities were found to be extremely high, with values 100%-300% higher than normal unregulated streams in Colorado. However, only two sites were sampled on the Fryingpan for this study.

15. Miller Ecological Consultants. 2004. A Study of Macroinvertebrate Community Responses to Winter Flows on the Fryingpan River. Prepared for the Roaring Fork Conservancy.

Macroinvertebrate sampling was conducted on the Fryingpan in 2003 and 2004 to examine the impact of Ruedi Reservoir on biotic health. Thermographs, hydrographs, and macroinvertebrate samples showed that decreases in EPT taxa were observed after anchor ice formation. With similar air temperatures in the two winters on record, lower discharges in the 2002-2003 winter led to more anchor ice formation.

16. Miller Ecological Consultants. 2006. A Study of Macroinvertebrate Community Responses to Winter Flows on the Fryingpan River. Prepared for the Roaring Fork Conservancy.

This study focused on factors that influence benthic macroinvertebrate community structure in the Fryingpan River, particularly the formation of anchor ice during periods of low flow. The results of the study showed that winter discharge magnitude was the most important factor that influenced macroinvertebrate survival rates. Average winter base flows of 40 cfs in 2002-2003 caused benthic macroinvertebrate communities to decline while average flows of 74 cfs and 85 cfs in the following winters caused community health metrics to rebound. Discharge magnitude and air temperatures were found to work together to form anchor ice, and that anchor ice was at least possibly responsible for declines in macroinvertebrate health. The study concluded that average flows greater than 70 cfs seem to result in less anchor ice in the upper half of the river than flows of 40 cfs.

17. Malone and Emeric. 2007. Roaring Fork Stream Health Initiative: Frying Pan River. Prepared for the Roaring Fork Conservancy.

This report was prepared as a part of the Roaring Fork Stream Health Initiative; a three-year effort to assess habitat on 185 miles of stream within the Roaring Fork basin, including the Fryingpan River. Divided into segments and subdivided into reaches, each reach was assessed for instream and riparian habitat quality and given a score from high quality to severely degraded (with separate scores produced for each bank). Ten Fryingpan reaches were assessed from Ruedi to the confluence with the Roaring Fork. Scores varied dramatically by reach and by location (right or left bank, instream). In general the right bank of the Fryingpan was much more degraded than the left bank due to road impacts. No instream habitat was considered "High Quality" and only one reach downstream of Rocky Fork attained that rating.

18. Miller Ecological Consultants. 2008. Evaluation of Seven Castles Creek Sediment Inflow on the Fryingpan River. Prepared for the Roaring Fork Conservancy.

After a rainstorm in summer 2007 caused a large sediment inflow from Seven Castles Creek into the Fryingpan River this study was commissioned to determine if a flushing flow was required to mobilize fine sediment downstream. Sediment and benthic macroinvertebrate sampling showed that sediment distributions were similar to prior to the event and that while macroinvertebrate density had declined, the quality of the community was still rated as "fair". No flushing flow was recommended, but if any additional water was applied it should be at during the natural peak. Since high flows under the current hydrological regime are unlikely to mobilize sediment that caused the Fryingpan River to avulse, mechanical movement of larger clasts was recommended.

19. Roaring Fork Conservancy. 2013. Comprehensive Lower Fryingpan River Assessment 2013-2015.

In response to the Bureau of Reclamation's decision to proceed with water marketing on 19,585 acre feet of water in 2013, the Roaring Fork Conservancy commissioned this management document that establishes the purpose and need for more research on the Fryingpan River. Research concerning the health of the American Dipper, benthic macroinvertebrate communities, and the presence of didymo was called for to better understand the state of the ecosystem.

20. Malone, Delia G. 2014. Survey of American Dipper (Cinclus mexicanus) Distribution, Abundance and Reproductive Success as a Baseline Indicator of Stream and Riparian Health on the Fryingpan River, Basalt, Colorado. Prepared for the Roaring Fork Conservancy.

This report described the impacts of Ruedi Reservoir on the American Dipper, an aquatic songbird native to the Fryingpan valley. This report used health of the American Dipper as a proxy for riparian and stream health. The study found that diminished flooding flows and anthropogenic development in the stream corridor has simplified channel structure and degraded the forage quality that the Dipper relies on. Dippers are also sensitive to the presence of humans, and the presence of humans within 50m of nest sites would prevent feeding of nestlings.

21. Miller Ecological Consultants. 2014. Lower Fryingpan River Benthic Macroinvertebrate Study October 2013 and April 2014. Prepared for the Roaring Fork Conservancy.

This study replicated earlier benthic macroinvertebrate sampling conducted from 2001-2003, using a similar fall to spring Results were similar to the previous study, with only slight variation in functional feeding groups and a slight decline in taxa richness. Similar to the previous study, there is more complexity in benthic macroinvertebrate communities with more distance from the dam due to the constant temperature regime proximal to the reservoir outlet. Overall, the results indicate generally good stream conditions, but the reduced number of taxa could be a result of recent changes to the flow regime.

22. Colorado Mountain College Natural Resource Management Program. 2014. Didymo Survey, Lower Fryingpan River, Basalt Colorado. Prepared for the Roaring Fork Conservancy.

This report describes didymo surveys on the Fryingpan River undertaken in the summer of 2014. Samples were gathered in May before peak flows, July, and October. In early June after the first sampling event, runoff peaked at 760 cfs for three days and was above 400 cfs for almost two weeks. Results from the second sampling event showed a significant decrease in didymo cover at nine sites after the high flow event, especially in areas closer to Ruedi Dam. The author suggested that sustained floods above 700 cfs help scour the streambed and mitigate didymo blooms.

23. Colorado Mountain College Natural Resource Management Program. 2015. Didymo Survey, Lower Fryingpan River, Basalt Colorado. Prepared for the Roaring Fork Conservancy.

This was the second annual report of a didymo survey on the Fryingpan River. Similar to the previous report, three sampling events were conducted in May before peak flows, July, and October. Two hydrologic peaks; one peak 700 cfs that lasted for a day and another peak of 825 cfs that lasted for four days. Didymo biomass decreased at downstream sites but increased at upstream sites between sampling events. While didymo presence at reference sites increased from 2014 to 2015, this study indicated that sustained high discharge causes bedload migration and scouring of didymo from substrate.

Appendix B: Bedload transport modeling of the Fryingpan River

Bedload Transport Modeling on the Fryingpan River

1 Introduction

While previous studies have investigated the environmental flows to encourage fish spawning in the fall and spring (Nehring 1988; Miller Ecological Consultants 2003) and to prevent anchor ice buildup in the winter (Miller Ecological Consultants 2006), there has been less attention given to high flows in the late spring/early summer. Annual peak flows serve an important purpose by mobilizing fine sediment to prevent embeddedness of bed material, mobilizing large sediment to prevent buildup of didymo and other nuisance algae, distributing nutrients to overbank areas, and preventing vegetation of stream banks and channel bars.

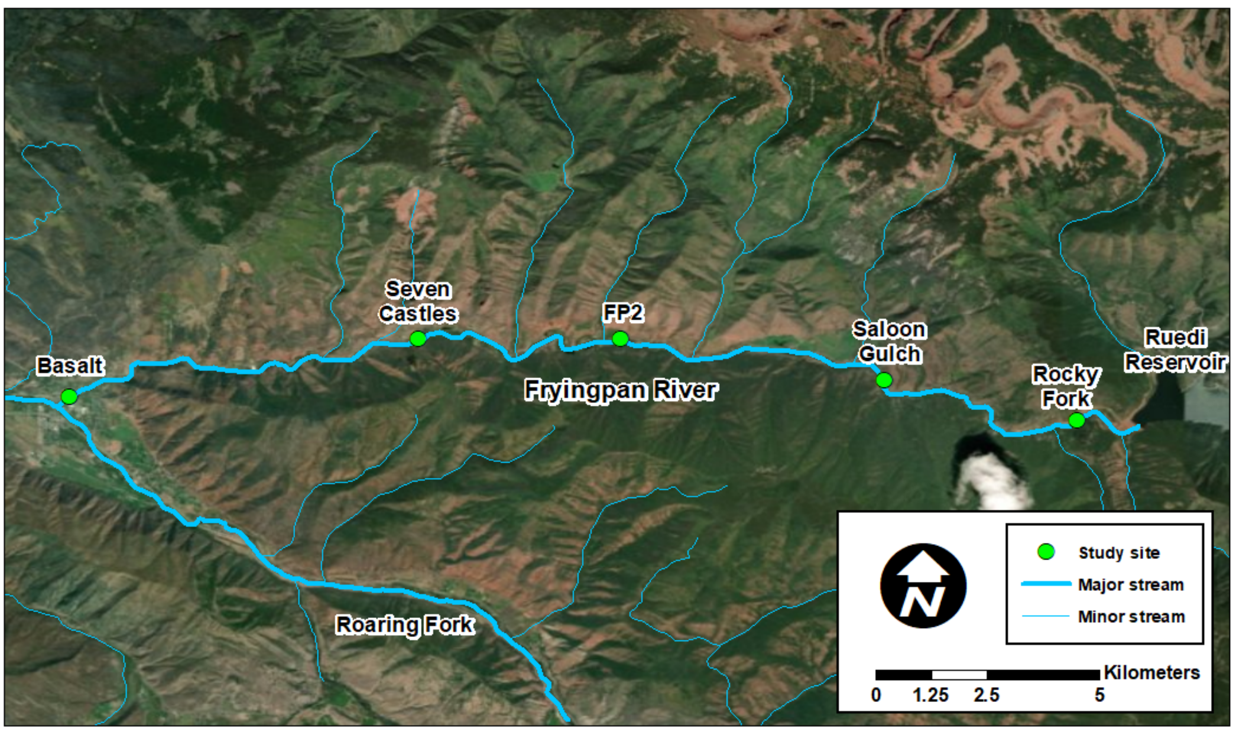

Figure 14: Location map of study sites used for bedload transport modeling on the Fryingpan River.

Bedload transport occurs only during high flows when the shear stress of the water acting on the streambed exceeds a certain threshold. The threshold for sediment transport in natural systems is usually only surpassed during floods or periods of high runoff, which can make direct sampling challenging and often dangerous. Therefore, sediment transport equations paired with field-measured parameters must be used to estimate the flows needed to mobilize sediment.

2 Methods

Five sites were selected that represented a range of geomorphic channel forms throughout the lower Fryingpan River. The study sites selected were; just downstream from Rocky Fork and Ruedi Dam, just upstream of Saloon Gulch at milepost 10, just upstream of milepost 7 (FP2), near Seven Castles Creek, and in downtown Basalt near the Swinging Bridge (Figure 3). First, parameters essential to estimating sediment transport were collected in the field or estimated using indirect methods. Cross-sectional profiles of the riverbed and banks were surveyed using the Emlid Reach GPS system. These profiles were then combined with lidar elevation data gathered in 2016 to create integrated bathymetric-topographic cross sections of the active river corridor. Grain size distributions of the riverbed material were gathered in the field, and the clasts were sorted into half-phi size fractions (e.g. >4 mm, 4-5.6 mm, 5.6-8 mm, etc.). In addition to field-measured parameters, channel slope is needed to estimate sediment transport. Channel slope was derived by extracting elevations along long profiles of the river from 3-foot resolution lidar DEMs gathered in 2016. The channel roughness parameter *n* (Manning's N) was estimated using a dimensionless relation derived from thousands of field measurements of bedload transport (Rickenmann & Recking 2011).

The cross-sectional profiles were virtually inundated with the desired water surface elevation using a spreadsheet model. The flow properties corresponding to each water surface elevation such as cross-sectional area, width, depth, and velocity were calculated using an iterative solution to the equations for continuity and flow resistance. In computing the flow properties for the desired water level, we assumed that channel slope, grain size and cross-sectional profile surveyed in the field were representative of conditions at higher flows.

Using this model, shear stress (τ) was calculated using the equation

$$\tau = \rho g \left(\frac{Q\,n}{B}\right)^{0.6} S^{0.7}$$

Where B denotes water surface width, ρ is the density of water, g is the gravitational constant, *n* is Manning's N, *Q* is the given discharge at that water surface, and S is reach slope.

The reference shear stress for size class i was evaluated with respect to the median grain size, D_{50}, using a hiding function,

$$\tau_{r_i} = \tau_{r_{50}} \left(\frac{D_i}{D_{50}}\right)^{\gamma}$$

where τ_{r50} is the reference shear stress for D_{50}, and γ is a parameter describing the extent to which transport is size-selective (= 0.0 implies τ_{ri} is independent of size). 0.018 is typically reported as a best fit value for the parameter γ (Parker & Klingeman 1982).

The equations for shear stress and reference shear stress were applied to a bed load transport equation (Parker & Klingeman 1982) to calculate a dimensionless bedload transport rate for size class i,

$$W_i^* = 11.2\left[1 - 0.853\frac{\tau_{r_{50}}}{\tau}\left(\frac{D_i}{D_{50}}\right)^{\gamma}\right]^{4.5}$$

Finally, the dimensionless transport rate was converted to a dimensional rate to indicate kilograms per second or tons per day.

Water surface elevations were modulated to determine the discharges necessary to initiate both fine fraction transport (grain sizes < 5.6 mm) and full bed mobility. A range of flows ranging from the threshold for full bed mobility and higher were used to create a water discharge-sediment discharge rating curve, an approach outlined in Forest Service guidance on determining flows required for channel maintenance (Schmidt & Potyondy 2004). This rating curve was then applied to the historical daily mean flow data for the Fryingpan River below Ruedi Reservoir (USGS gage 09080400) to determine the geomorphic work caused by each discharge.

In addition to bedload sediment transport modeling, we used a flood frequency estimation approach to determine the magnitude of floods on the Fryingpan River that correspond to given recurrence intervals (i.e. 2-year flood, 10-year flood, etc). A Log Pearson Type III distribution was used to fit observed annual high flow events to a line of best fit and create a rating curve, per US Geological Survey guidance (England Jr. et al. 2019). A 99% confidence interval was used to establish upper and lower limits to the flood frequency curve.

3 Results

Sites were chosen based on their geomorphic characteristics and location within the Fryingpan watershed (Figure 3). Rocky Fork, the uppermost site, is located immediately downstream of Ruedi Reservoir. It is a pool-riffle reach with a hardened right bank due to an access road. The Saloon Gulch Site is in a plane bed reach featuring varying types of rapids. The stream is also constrained on river right by Fryingpan Road. The FP2 site is in a step-pool reach with a small medial bar and confinement by the road on the right bank. The Seven Castles site is in a low-gradient pool section of the Fryingpan and is part of a valley-wide wetland complex. Willows and a pond are adjacent to the reach on river left while the road provides a hard barrier on the right bank. The Basalt site is a high-gradient plane bed reach that flows through the town of Basalt. The site is just downstream of the Swinging Bridge in Basalt and is constrained by reinforced urban development on both sides including homes, businesses, and bridge pilings.

Site characteristics for the five study sites varied widely with distance downstream. Slopes ranged from 0.049% at Seven Castles to 1.83% at Saloon Gulch. Median grain size ranged from 13 mm at Seven Castles to 108 mm at Saloon Gulch (Table 1). D_{84}, or the sediment size greater than 84% of the total bed material, ranged from 22 mm at Seven Castles to 264 mm at Saloon Gulch.

Table 4: Comparison of site characteristics and transport thresholds for the five study sites.

	Rocky Fork	Saloon	FP2	7 Castles	Basalt
Full Mobility (cfs)	564	707	795	548	375
Sand (< 5.6mm) (cfs)	454	531	630	538	304
Slope	0.0067	0.0183	0.0126	0.00049	0.0106
D84 GS (m)	0.173	0.264	0.21	0.022	0.186
D50 GS (m)	0.092	0.131	0.121	0.014	0.091
Median GS (m)	0.0810084	0.108383	0.107262	0.013041	0.070818

Thresholds for both fine fraction transport and full bed mobility ranged widely (Table 1). Downstream sites at Seven Castles and in Basalt had much lower thresholds for transport than the sites at Rocky Fork, FP2, and Saloon Gulch. The threshold flow that mobilized all sediment at the majority of sites was 707 cfs. This flow was sufficient to mobilize the full range of grain sizes at three of the five sites. The flow that mobilized the fine fraction (< 5.6 mm) of bed sediment at four of the five sites was 531 cfs. The FP2 site had much higher thresholds for transport than the other sites (Table 1).

Flood frequency analysis of observed peak flows on the Fryingpan River shows a regulated system with a relatively tight distribution of peak flows (Figure 4). Very few extreme flows have been observed over the duration of the gage record. The 2-year flood often approximates the "bankfull" flow, a concept useful in natural systems but somewhat irrelevant in altered systems such as the Fryingpan. The flow corresponding to the 2-year return period is 697 cfs (Figure 4).

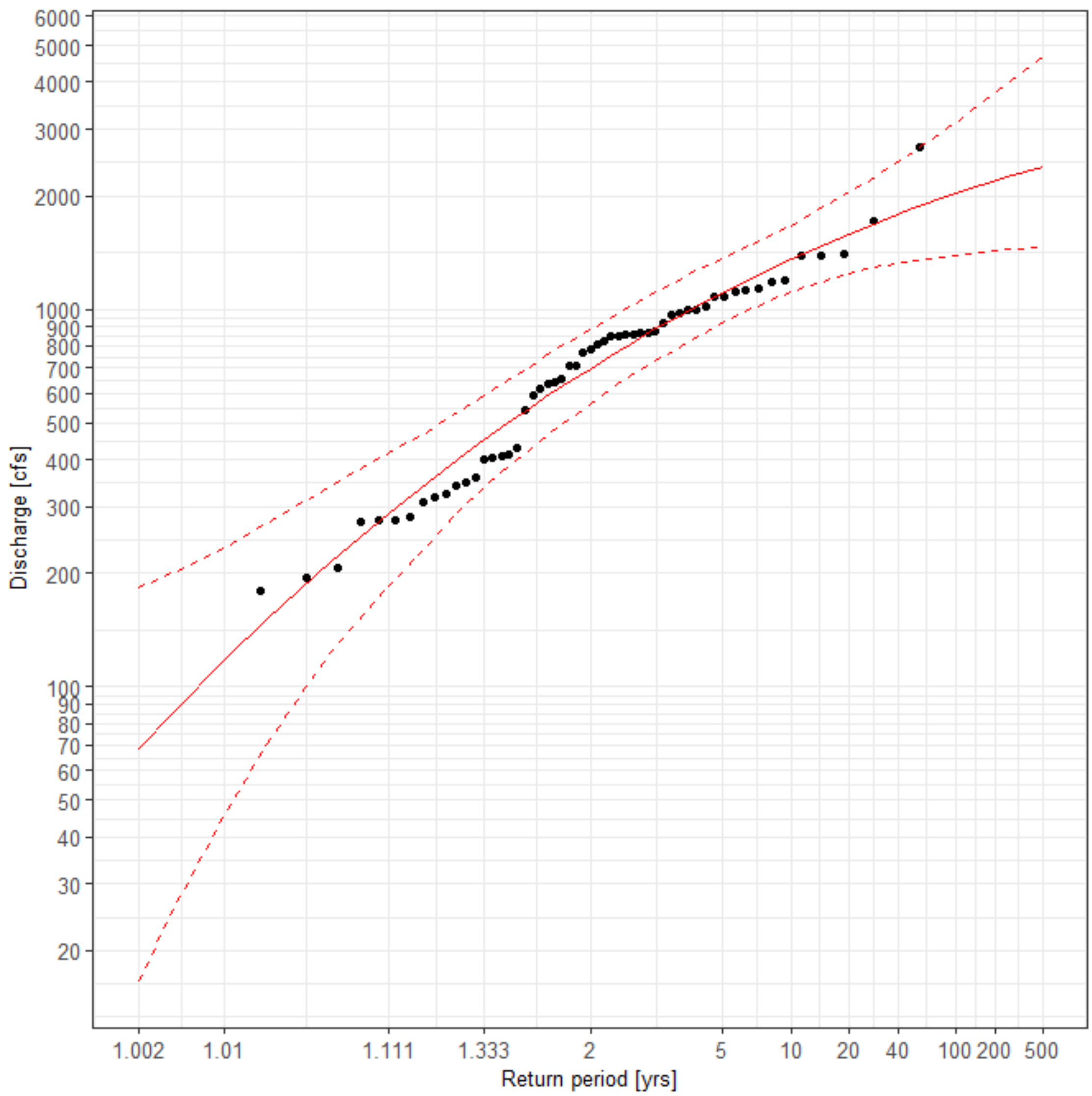

Figure 15: Flood frequency curve for the Fryingpan River with line of best fit and 99% confidence intervals (dashed).

A bedload rating curve for the Saloon Gulch site was determined by altering the water surface elevations in the bedload transport model for flows ranging from the threshold for transport of the median grain size class to a discharge slightly larger than the highest flow ever released from Ruedi Reservoir (1400 cfs) (Figure 3). The bedload transport model at Saloon Gulch showed that 607 cfs was the threshold flow to transport the median grain size (108 mm). The power law trendline that fit the data best had a coefficient of 1×10^{-8} and an exponent of 3.44 (Figure 5).

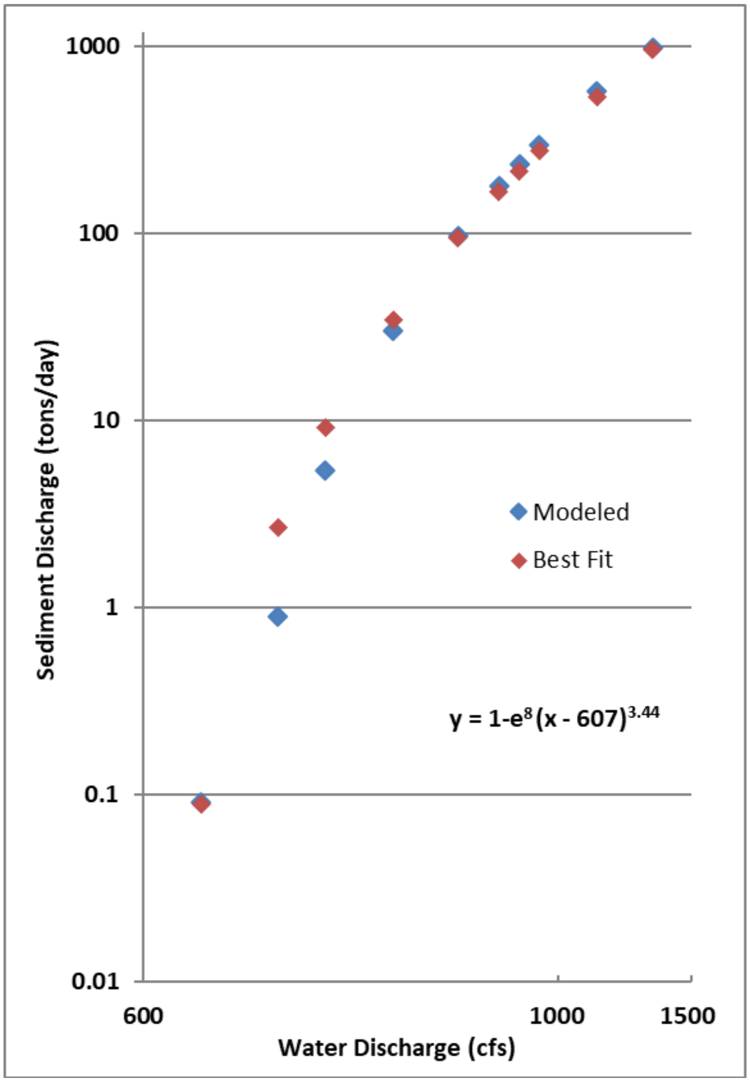

Figure 16: Modeled bed load transport values and bedload transport rating curve best fit values for discharges ranging from the median grain size transport threshold (607 cfs) to the highest release ever from Ruedi Reservoir (1400 cfs).

Since the last management plan for Ruedi Reservoir was adopted in 1989, mean daily flows have been 1,085 cfs or lower. The bedload sediment rating curve was applied to the historical record of mean daily discharge from 1989-2019, an approach known as a magnitude-frequency analysis (Schmidt & Potyondy, 2004). Magnitude-frequency analysis results were normalized by the total days and total sediment volume calculated throughout the period of record. Between 1989 and 2019 the threshold for transport was exceeded for a total of 182 days, or an average of ~9 days/year. 95.7% of the total bed load was transported by flow greater than 785 cfs. Flows between 785 and 935 cfs accounted for 45.3% of the bedload transport during 38.5% of the time above threshold (Figure 6). Flows greater than 935 cfs accounted for 50.3% of the total bedload transport despite only occurring 8.3% of the time (Figure 6).

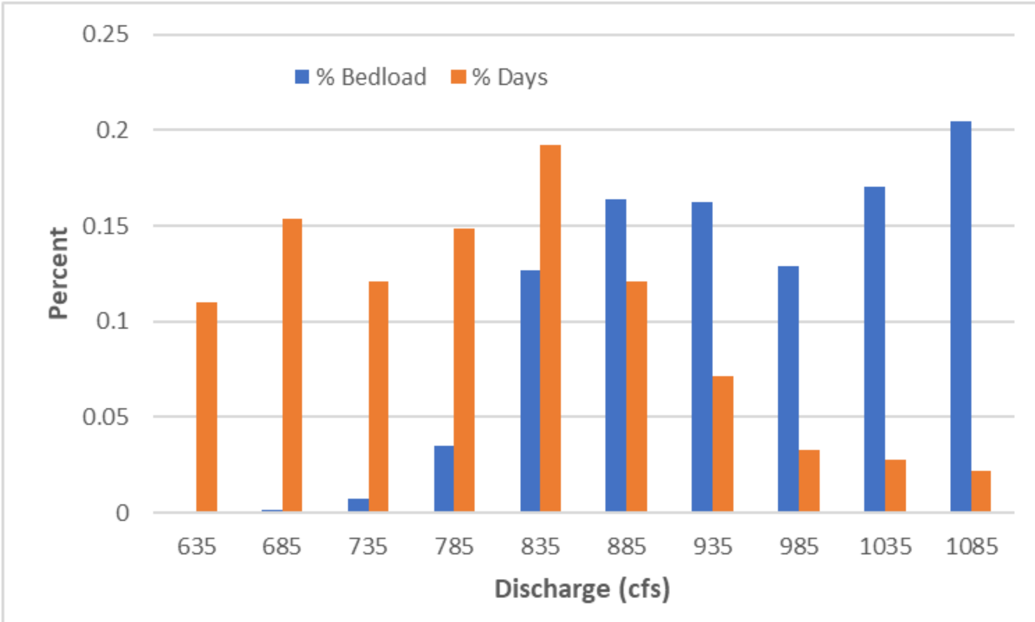

Figure 17: Normalized magnitude-frequency graph of bedload transport and time as a percentage of the total. Discharge bins represent the high value.

4 Discussion

One of the main ecological functions of high flows is the movement of sediment. With sediment mobilization as a goal, our bedload transport model points to specific flows for mobilization of fine sediment and all size classes. A flow of 707 cfs would lead to full bed mobility at four of the five sites, and presumably a large percentage of the river area. A flow of 530 cfs would mobilize fine bed particles (< 5.6 mm) at four of the five sites.

Variability in transport thresholds at the five sites is to be expected due to site characteristics and natural variability in channel geometry. Site-specific characteristics could account for the much lower thresholds for transport at the Basalt site, which has both a steep gradient and is channelized on both sides to protect structures. This combination of factors is probably responsible for the low mobilization thresholds. Channelization by levees and bank stabilization has been shown to lead to vertical incision of the streambed in dam-controlled river systems (Leonard et al. 2017), which may lead to a new equilibrium state with lower channel slope.

The flood frequency analysis of peak flows for the Fryingpan River also shows that the 2-year flood is 697 cfs (Figure 4). The similarity of this flow to the calculated threshold for full bed mobility is an interesting coincidence. While this cannot be referred to as the “bankfull” flow due to the hydrologically altered state of the Fryingpan River, the 2-year flood is a good indicator of the typical high flow. Gravel-bedded channels are known to self-adjust to changes in the hydrologic regime, and channels typically adjust to the boundaries set by the most frequent high flow. In this case, the flow of ~700 cfs seems to be a key flow for both sediment transport and flood frequency.

While 700 cfs is the trigger flow for the majority of the sites for full bed mobility, results from the magnitude-frequency analysis indicate that the majority of sediment is moved at higher flows despite fewer days at those flows. An ideal magnitude-frequency plot features a single peak of sediment moved at an intermediate discharge, but the plot for the Fryingpan River has two peaks (Figure 6). This is most likely due to the truncation of high flows by Ruedi Reservoir and the Fry-Ark Project.

The few years of gage records available from before the construction of Ruedi Reservoir show that peak flows above 1,000 cfs occurred annually, with one-year peaking at 2,680 cfs (Figure 2). Natural snowmelt cycles also caused higher flows to persist for a longer period than at present. In contrast, 2019 was the first year since 1997 where peak flows exceeded 1,000 cfs below Ruedi Reservoir. Truncation of peak flows leads to an alteration of the hydrograph and therefore impacts the magnitude-frequency analysis. Our analysis shows that flows above 985 cfs are much more efficient at transporting sediment but flows between 785-935 cfs occur much more frequent and therefore cause a large fraction of sediment transport (Figure 6).

Appendix C: Web Application Access

Access Points for Web Applications

Conceptual Model:

https://insightmaker.com/insight/203840/Riverine-Ecosystem-Model-for-the-Fryingpan-River

Roaring Fork River Temperature Prediction Model:

https://lotic.shinyapps.io/RoaringFork_WaterTemps/

Fryingpan River Streamflow Prediction Model:

https://lotic.shinyapps.io/Fryingpan_Flow_Predictions/