STUDY PLAN TO IDENTIFY PEAK FLOW REQUIREMENTS FOR SEDIMENT TRANSPORT AND HABITAT MAINTENANCE IN THE UPPER COLORADO RIVER BASIN

Prepared by the Upper Basin Peak Flow Working Group

Kirk LaGory, Argonne National Laboratory
Tom Chart, Upper Colorado River Endangered Fish Recovery Program
Jana Mohrman, U.S. Fish and Wildlife Service
John Pitlick, University of Colorado-Boulder
Cory Williams, U.S. Geological Survey (USGS)
J. Toby Minear, USGS
John C. Schmidt, USGS Grand Canyon Monitoring and Research Center (GCMRC)
David Topping, USGS GCMRC
Paul Grams, USGS GCMRC
Blair Greimann, Bureau of Reclamation
Tom Pitts, Water Users Representative
Daniel F. Luecke, Environmental Representative

Coordinated by

Upper Colorado River Endangered Fish Recovery Program

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EXECUTIVE SUMMARY

Four endemic endangered fishes of the Upper Colorado River Basin (bonytail, *Gila elegans*, Colorado pikeminnow, *Ptychocheilus lucius*, humpback chub, *G. cypha*, and razorback sucker, *Xyrauchen texanus*) are found in the Upper Colorado River Basin. Peak river flows play a critical role in maintaining a dynamic river system that supports these and other native aquatic species. A critical component of published flow recommendations was identification of the magnitude, duration, frequency, and timing of peak flows needed to maintain in-channel and floodplain wetland habitats essential for meeting related life history requirements of these species. While these recommendations identified anticipated effects of peak flows, associated uncertainties, and priorities for research, there is now a need to reassess, prioritize, and integrate specific research needs based on information gathered since the recommendations were published to resolve uncertainties, monitor effects of recommended flows, and provide a strong scientific basis for future peak flow requirements and their eventual protection.

An ad hoc working group of geomorphologists, biologists, and hydrologists was convened by the Upper Colorado River Endangered Fish Recovery Program (Recovery Program) to perform these tasks and develop a study plan to address peak flows. To accomplish this, the working group (1) reviewed previously identified uncertainties, and research that has been conducted to date to resolve these uncertainties in the basin, (2) reviewed current research techniques that could be applied to resolving remaining uncertainties, and (3) developed a focused study plan (this report) to monitor peak flow-related responses and address remaining uncertainties.

The working group proposed a targeted, hypothesis-based monitoring and research program to address four peak flow topics: (1) peak flows needed to maintain the connection of floodplain wetlands to the main channel; (2) peak flows needed to prevent channel narrowing; (3) peak flows needed to maintain spawning habitats and other gravel and cobble-bed benthic habitats; and (4) peak flows needed to build and maintain connected backwater habitats. All of these topics are considered high priority and necessary for establishing scientifically based peak flow recommendations. However, priorities do vary among rivers and reaches within those rivers.

Five hypotheses were proposed for testing under this study plan:

H_1: Peak flow magnitude, duration, frequency, and timing affect long-term maintenance of connection of priority floodplain wetlands to the main channel of the Green, Gunnison, and Colorado Rivers.

H_2: Peak flow magnitude, duration, frequency, and timing affect channel width in the Green, Gunnison, and Colorado Rivers.

H_3: Peak flow magnitude, duration, frequency, and timing affect the suitability of spawning habitats in the Green, Gunnison, and Colorado Rivers.

H_4: Peak flow magnitude, duration, frequency, and timing affect the productivity of gravel and cobble-bed benthic habitats in the Green, Gunnison, and Colorado Rivers.

H_5: The effect of peak flow magnitude, duration, frequency, and timing on suspended sediment transport and fine sediment mass balance affect the abundance and characteristics of connected backwater habitats in the Green and Colorado Rivers.

The objective of studies developed under this plan would be to quantify the degree to which any reductions in peak flows would result in loss or degradation of fish habitats.

The study plan includes a mix of ongoing monitoring and periodic or short-term focused research designed to address these five hypotheses. The specific objectives, tasks, and expected outcomes for individual studies developed under this plan will be identified in statements of work approved by the Recovery Program. These projects and the resulting project reports will go through the standard Recovery Program review protocols. It is anticipated that in addition to an annual review of the data collected, a synthesis report will be developed after the first 5 years of the study that summarizes results from individual projects, integrates results, summarizes conclusions, and makes recommendations for future management of peak flows in the Upper Basin. As for any study plan, additional knowledge will be gained during implementation, and it will be important to have enough flexibility to adjust studies and overall approaches in response to this new information. Toward this end, the results of studies will be evaluated each year to determine the need for modification.

This study plan was drafted by an ad hoc working group, which included representatives from Reclamation, U.S. Geological Survey, University of Colorado-Boulder, U.S. Fish and Wildlife Service, Argonne National Laboratory, and environmental interests. Development of the study plan was coordinated by the Recovery Program.

1 INTRODUCTION

Four endemic endangered fishes of the Upper Colorado River Basin (bonytail, *Gila elegans*, Colorado pikeminnow, *Ptychocheilus lucius*, humpback chub, *G. cypha*, and razorback sucker, *Xyrauchen texanus*) are found in the Upper Colorado River Basin. Flow recommendations for these fishes in the three largest rivers of the basin (Green, Gunnison, and Colorado Rivers) were identified in a series of reports developed by the Upper Colorado River Endangered Fish Recovery Program (Muth et al. 2000; McAda 2003). Peak river flows play a critical role in maintaining a dynamic river system that supports these and other native aquatic species. A critical component of flow recommendations was identification of the magnitude, duration, frequency, and timing of peak flows needed to maintain in-channel and floodplain wetland habitats essential for meeting life history requirements of these species. Peak flows provide the energy needed to mobilize and transport sediment, remove fine sediments from spawning areas, build and maintain in-channel backwater nursery habitats, and scour encroaching vegetation that could lead to channel narrowing and simplification. Peak flows also inundate off-channel habitats such as floodplain wetland nursery habitats and provide an opportunity for fish larvae to colonize those nursery habitats and later escape to the main channel river to complete their life cycle.

Tiering from the flow recommendation reports were study plans for the Green River (Green River Study Plan Ad Hoc Committee 2007) and Gunnison and Colorado Rivers (Aspinall Study Plan Ad Hoc Committee 2011), as well as a geomorphology research priorities report for the Upper Basin (LaGory et al. 2003). The Recovery Program has used these reports as the basis for identifying and funding projects to monitor the response of the river systems and fish populations to implementation of recommended flows and to address uncertainties associated with the recommendations. While these plans identified anticipated effects of peak flows, associated uncertainties, and priorities for research, there is now a need to reassess, prioritize, and integrate specific research needs to resolve uncertainties, monitor effects of recommended flows, and provide a strong scientific basis for future peak flow requirements and their eventual protection.

An ad hoc working group of geomorphologists, biologists, and hydrologists was convened by the Recovery Program to perform these tasks and develop a study plan to address peak flows. To accomplish this, the working group (1) reviewed previously identified uncertainties, and research that has been conducted to date to resolve these uncertainties in the basin, (2) reviewed current research techniques that could be applied to resolving remaining uncertainties, and (3) developed a focused study plan (this report) to monitor peak flow-related responses and address remaining uncertainties.

Tables 1, 2, and 3 summarize the anticipated effects, uncertainties, and priorities identified in the study plans and geomorphology priorities report. Not surprisingly, there was some consistency in the high priority research needs identified in these reports. To summarize, the following high priority research needs were identified in one or more of the reports:

TABLE 1 Green River Study Plan—High Priority Anticipated Effects and Uncertainties Associated with Recommended Peak Flows

Anticipated Effects	Uncertainties
Floodplain Wetlands	
Wet and Moderately Wet Years: Significant inundation of floodplain habitat and off-channel habitats (e.g., tributary mouths and side channels) to establish river-floodplain connections and provide warm, food-rich environments for growth and conditioning of razorback suckers (especially young) and Colorado pikeminnow. Average Years: Significant inundation of floodplain habitat and off-channel habitat in at least 1 of 4 average years; some flooding of off-channel habitats in all years. Moderately Dry and Dry Years: No floodplain inundation, but some flooding of off-channel habitats. May benefit recruitment of Colorado pikeminnow in some years (Muth et al. 2000).	Flow and stage at which floodplains with levee breaches become sufficiently inundated (area, depth, volume) to provide nursery habitat for razorback suckers. Rates of sediment deposition and erosion in breaches and floodplain depressions as a function of breach configuration, peak flow, and connecting flow magnitude and duration
Connected Backwaters Base flows in summer and autumn scaled to the hydrologic condition favor the formation of backwaters and other low-velocity shoreline nursery habitats (Muth et al. 2000). Source: Green River Study Plan Ad Hoc Committee 2007	The effect of peak flows, sediment availability, and antecedent conditions on the relationship between base flow level and backwater habitat availability.

Floodplain Wetlands

- Flow and stage at which floodplains with levee breaches become sufficiently inundated (area, depth, volume) to provide nursery habitat for razorback suckers (Green and Colorado Rivers).

- Rates of sediment deposition and erosion in breaches and floodplain depressions as a function of breach configuration, peak flow, and connecting flow magnitude and duration (Green, Colorado, and Gunnison Rivers).

- The ability of partial restoration of floodplain function to benefit endangered fishes (Colorado River).

In-Channel Habitats

- Frequency of periodic, channel-wide flushing of cobble bars that is necessary to maintain habitat (Gunnison River).

TABLE 2 Gunnison and Colorado Rivers Study Plan—High Priority Anticipated Effects and Uncertainties Associated with Recommended Peak Flows

Anticipated Effects	Uncertainties and Priorities for Research
In-Channel Habitat Maintenance	
Wet years: Significant motion of the river bed is exceeded for an extensive time period, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in wide areas of the river. Vegetation encroachment will be halted and reversed in wide areas of the river.	Frequency of periodic, channel-wide flushing of cobble bars that is necessary to maintain habitat in the Gunnison River.
Moderately Wet and Average Wet Years: Significant motion of the bed is reached, and will help maintain in-channel habitats used by endangered fishes, and slow or prevent channel narrowing. Widespread areas with clean substrate should provide habitat needed for maximum reproductive success of Colorado pikeminnow, razorback sucker and humpback chub, and increased primary and secondary production.	Frequency and duration (number of days) of flows above half-bankfull and bankfull thresholds to maintain habitats required by the endangered fishes in the Gunnison River. Relationship between fine sediments and primary and secondary production in the Gunnison River.
Average Dry Years: Initial motion (but not significant motion) of the bed is reached, and results in some scouring of gravel and cobble bars. Areas with clean substrates for egg deposition and incubation should provide habitat needed for reproduction of Colorado pikeminnow, razorback sucker, and humpback chub, and increased primary and secondary production. Significant motion is not reached,	*Note: Uncertainties associated with channel maintenance in the Colorado River were identified as Medium Priority.*
Moderately Dry and Dry Years: No channel maintenance will occur unless initial motion thresholds are reached. However, these thresholds should be reached during at least some years within this category in order to improve main channel habitats	
Floodplain Wetlands	
Wet and Moderately Wet Years: Floodplain inundation will be extensive. The duration of flows greater than bankfull flow will ensure that floodplain area is available to improve growth and survival of YOY razorback suckers. The duration of flows exceeding bankfull will ensure that YOY razorback sucker will be able to utilize floodplain habitats for sufficient time to increase their growth and survival.	The ability of partial restoration of floodplain function to benefit endangered fishes in the Colorado River. The relationship of habitat availability to peak-flow and base-flow magnitude in the Palisade to Gunnison River and Gunnison River to Loma reaches of the Colorado River.
Average Wet Years: Floodplain inundation will occur but be brief.	
Average Dry and Moderately Dry Years: Some warm quiet-water habitats will be provided for growth and gonad maturation of endangered fish. The backwater at Walker SWA will provide some of this quiet habitat.	*Note: Uncertainties associated with floodplain wetlands in the Gunnison River were identified as Medium Priority.*
Dry Years: No floodplain inundation will occur, but some inundation of tributary mouths may occur.	

Source: Aspinall Study Plan Ad Hoc Committee 2011

TABLE 3 Geomorphology Research Priorities Report—Primary Peak Flow-Related Information Needs for the Upper Colorado River Basin

Uncertainties	River/Reach (River Mile)
Floodplain Wetlands	
Effects of peak flow (magnitude, duration, frequency, and timing), sediment, and configuration of connection to main channel on maintenance of connection and sediment deposition effects	Green River • Split Mountain Canyon to Desolation Canyon (RM 216-319) Colorado River • Palisade to Gunnison (RM 171-185) • Gunnison to Loma (RM 154-171) Gunnison River • Hartland Dam to Roubideau Creek (58-66)
The relationship of habitat availability to peak-flow and base-flow magnitude	Colorado River • Palisade to Gunnison (RM 171-185) • Gunnison to Loma (RM 154-171)
Spawning Bars	
Effects of peak flow (magnitude, duration, frequency, and timing), base flow (magnitude and duration), and sediment on habitat conditions during the spawning period	Green River • Split Mountain Canyon to Desolation Canyon (RM 216-319) • Desolation and Gray Canyons (RM 132-216) Colorado River • Palisade to Gunnison (RM 171-185) • Gunnison to Loma (RM 154-171) • Loma to Westwater (RM 125-154) • Westwater Canyon (RM 113-125) • Cottonwood Wash to Dewey Bridge (RM 94-113) • Moab Bridge to Green River (RM 0-64) Gunnison River • Hartland Dam to Roubideau Creek (RM 58-66) • Roubideau Creek to Colorado River (RM 0-58)
Connected Backwaters	
Role of peak flow (magnitude, duration, frequency, and timing) and sediment on formation and maintenance of habitats Effects of antecedent conditions (flow and sediment) and base-flow magnitude on habitat availability	Green River • Split Mountain Canyon to Desolation Canyon (RM 216-319) • Gray Canyon to Labyrinth Canyon (RM 92-132) • Labyrinth and Stillwater Canyons (RM 0-92) Colorado River • Cottonwood Wash to Dewey Bridge (RM 94-113) • Jackass Canyon to Moab Bridge (RM 64-70) • Moab Bridge to Green River (RM0-64)

Source: LaGory et al. 2003

- Frequency and duration (number of days) of flows above half-bankfull and bankfull thresholds to maintain habitats required by the endangered fishes (Gunnison River).

- Relationship between fine sediments and primary and secondary production (Gunnison River).

- The effect of peak flows, sediment availability, and antecedent conditions on the relationship between base flow level and backwater habitat availability (Green and Colorado Rivers).

- Effects of peak flow (magnitude, duration, frequency, and timing), base flow (magnitude and duration), and sediment on habitat conditions during the spawning period (Green, Colorado, and Gunnison Rivers).

LaGory et al. (2003) also identified the highest priority reaches where information needs should be addressed (Table 3). The priority assigned to reach-specific information needs was a function of each reach's importance (either actual or potential) in supporting specific life history stages of endangered fishes and the degree of uncertainty associated with peak-flow related parameters in those reaches. The location of specific habitats is largely related to channel morphology (alluvial valleys vs. canyon-bound portions of the river) and other factors (e.g., substrate, temperature, and primary and secondary productivity). Thus, off-channel floodplain wetland nursery habitats typically are found in broad alluvial reaches of Upper Basin rivers. Connected backwaters form behind sandbars and are found in low-gradient meandering, usually alluvial, sand-bedded river segments. In-channel spawning bars are located in higher gradient, gravel and cobble-bed reaches. Peak flows perform very different functions in these different reaches and habitats, and these different functions inform the proposed monitoring and research presented in the next section.

2 PROPOSED MONITORING AND RESEARCH

Maintaining the frequency, magnitude, duration, and timing of peak flows needed to sustain functioning habitats that support populations of the endangered fishes of the basin was the intent of peak flow recommendations developed by the Recovery Program. These recommendations identified magnitude, duration, and frequency needed to connect floodplain nursery habitats, prevent or reverse vegetation encroachment and channel narrowing, maintain suitable spawning habitat, maintain productive benthic substrates, and build and maintain suitable backwater nursery habitats. Each of these peak flow functions and a proposed approach to the study of remaining high priority uncertainties is described next. Identifying and verifying the values of these variables in different rivers and reaches is the intent of the monitoring and research identified in this study plan.

We propose a targeted, hypothesis-based monitoring and research program. The topics to be examined under the study plan, hypotheses to be tested within each, and the general methods to be employed are described here and summarized in Table 4. Four peak flow topics are included in this plan: (1) peak flows needed to maintain the connection of floodplain wetlands to

TABLE 4. Peak Flow Study Plan Topics, Hypotheses, Variables, Related Studies, and Priorities

Topics, Hypotheses, and Priorities	Variables and Priorities	Related Studies and Data [(a)]
Floodplain Wetland Connection to the Main Channel (Priority: High)		
H_1: Peak flow magnitude, duration, frequency, and timing affect long-term maintenance of connection of priority floodplain wetlands to the main channel of the Green, Gunnison, and Colorado Rivers (Priority: High)	High priority: Flows needed to connect priority floodplain wetlands in the Green River	Larval trigger study plan and associated studies. Recently completed survey of levee breaches and inflow channels following high peak flows in 2011. Similar survey should be conducted following high-magnitude peak flows (e.g., > 20,000 cfs).
	Medium priority: Flows needed to connect priority floodplain wetlands in the Gunnison and Colorado River	New study needed to assess connection of priority wetlands (Escalante State Wildlife Area, Walker State Wildlife Area) on an annual basis and following high magnitude peak flows (>14,000 cfs in Gunnison and >35,000 cfs in the Colorado River).
Channel Narrowing (Priority: High)		
H_2: Peak flow magnitude, duration, frequency, and timing affect channel width in the Green, Gunnison, and Colorado Rivers (Priority: High)	Changes in channel width through time as a function of peak flow magnitude, duration, frequency, and timing in study reaches: High priority: Middle Green River (Split Mountain to Desolation Canyon), Lower Gunnison River (Hartland Dam to Colorado River), Middle Colorado River (Gunnison River to Loma), Medium priority: Lower Green River (Gray Canyon to Colorado River), Lower Colorado River (Loma to Green River)	Larval trigger study plan and associated studies. New study needed to evaluate aerial imagery of study reaches in the Green, Gunnison, and Colorado Rivers or an analysis of cross-section information near USGS streamflow gages.

Table 4 (Cont.)

Topics, Hypotheses, and Priorities	Variables and Priorities	Related Studies and Data [(a)]
Spawning and Benthic Habitats (Priority: High)		
H_3: Peak flow magnitude, duration, frequency, and timing affect the suitability of spawning habitats in the Green, Gunnison, and Colorado Rivers.	Relationship between peak flow magnitude and direct measurements of bed load transport (focused study). Hydrophone readings, either calibrated to direct measurements of bed load transport or used without calibration to determine the onset of bed movement (monitoring). Sediment transport and mass balance in critical reaches (monitoring). Relationship between peak flow magnitude and movement of painted or RFID tagged cobbles (alternate approach) High priority: Lower Gunnison River (Hartland Dam to Colorado River), Middle Colorado River (Palisade to Loma) Medium priority: Lower Colorado River (Loma to Green River), Lower Green River (Desolation and Gray Canyons)	New study needed to evaluate bed load transport, fine sediment mass balance, and depth to embeddedness in gravel and cobble-bed portions of the Gunnison and Colorado Rivers. Project 85f resolved uncertainties related to a critical Green River spawning bar in the Split Mountain to Desolation Canyon reach.
H_4: Peak flow magnitude, duration, frequency, and timing affect productivity of other gravel and cobble-bed benthic habitats in the Green, Gunnison, and Colorado Rivers.	Depth-to-embeddedness. Medium priority: Lower Gunnison River (Hartland Dam to Colorado River), Middle Colorado River (Palisade to Loma)	Ongoing study addressing benthic habitat conditions and productivity in the lower Gunnison River. If needed, new field studies in the Gunnison and Colorado Rivers could tier from this.
Connected Backwater Habitats (Priority: High)		
H_5: The effect of peak flow magnitude, duration, frequency, and timing on suspended sediment transport and fine sediment mass balance affect the abundance and characteristics of connected backwater habitats in the Green and Colorado Rivers.	Suspended sediment transport and fine sediment mass balance in critical reaches (monitoring). High priority: Middle Green River (Split Mountain Canyon to Desolation Canyon) Medium priority: Middle Colorado River (Cottonwood Wash to Dewey Bridge)	Tier from existing USGS-GCMRC acoustic sediment monitoring program adding gage at Ouray, Utah. Existing backwater synthesis project will summarize existing information. Larval trigger study plan identified the need for similar studies.

the main channel; (2) peak flows needed to prevent channel narrowing; (3) peak flows needed to maintain spawning habitats and productive benthic habitats; and (4) peak flows needed to build and maintain connected backwater habitats. Some topics are best addressed with ongoing monitoring or with periodic or short-term focused research designed to answer specific questions.

As identified in Tables 1-3, there are differences in the priorities assigned to different topics, and in different rivers and reaches. We reexamine priorities based on current knowledge and research conducted since the study plans were developed and implemented. It is important to note that the priorities assigned to topics in this study plan are relative to their importance to resolving peak flow uncertainties and not to overall priorities of the Recovery Program. Wherever possible, the study plan identifies existing projects that could be modified or expanded to test hypotheses, in order to capitalize on well-established protocols. Costs for new projects are described below and presented in the Appendix.

FLOODPLAIN WETLAND CONNECTION TO THE MAIN CHANNEL

Floodplain wetlands serve a variety of important ecological functions that can benefit endangered fishes of the system if these wetlands are connected to the main channel often enough. Important floodplain wetland habitats are found mainly in the middle Green River between Split Mountain Canyon and Desolation Canyon, but also in the lower Gunnison and middle Colorado River. Table 3 presents the reaches identified in LaGory et al. (2003) where understanding the role of peak flows on maintaining floodplain wetland connection was considered a primary information need.

Floodplain wetlands are important nursery habitats for the razorback sucker, and it is assumed that peaks flows of sufficient magnitude, duration, and frequency and that occur at appropriate times of the year to fill the needs of this species would also benefit the other endangered fishes. The current study plan, with its focus on sediment transport and habitat maintenance does not focus on the timing of connection needed to fulfill the needs of species, but rather timing as it relates to sediment transport. Species needs are addressed in the larval trigger study plan (Larval Trigger Study Plan Ad Hoc Committee 2012)

The hypothesis[1] to be tested for floodplains is:

H_1: Peak flow magnitude, duration, frequency, and timing affect long-term maintenance of connection of priority floodplain wetlands to the main channel of the Green, Gunnison, and Colorado Rivers.

Recently, the Program developed a study plan for the Green River to address the response of razorback suckers to peak flows timed to coincide with the presence of drifting larvae (Larval Trigger Study Plan Ad Hoc Committee 2012). That study plan addressed the questions related to flow magnitude, duration, frequency, and timing related to connecting priority floodplain

[1] All hypotheses are written as null hypotheses, i.e., that there is no effect of peak flows on the parameters being considered.

wetlands, including the long-term maintenance of those connections, and is considered sufficient to address those functions of peak flows in the Green River. These information needs were addressed in the larval trigger study plan under the hypothesis "*Entrainment and retention of larvae in floodplain wetlands are not related to the magnitude of connecting flows when larvae are present*."

As described in the larval trigger study plan, monitoring of a set of priority wetlands should be conducted annually to determine the actual connecting flow that occurs in a given year, and periodically to determine if antecedent peak flows have altered the magnitude of the connecting flow either through deposition or scouring of levee breaches and inflow channels.[2] As suggested in that plan, a new field study to collect these data could tier from project C6-hydro. Similar studies have not been undertaken in the Gunnison and Colorado Rivers, but are identified here as medium priority.

To evaluate changes in connection flows after the high peak flows of 2011, staff from Western Area Power Administration, Argonne National Laboratory, and U.S. Fish and Wildlife Service (USFWS) surveyed levee breaches in eight priority wetlands in the middle Green River. They determined that most upstream and downstream breaches showed evidence of significant fill with alluvial sand and debris since the last survey was completed in 2005 (TetraTech 2005). In general, downstream breaches had lower elevations and connection flows than upstream breaches. The downstream breach and inflow channels of two wetlands (Escalante and Old Charley Wash) showed reductions in elevation and subsequent decrease in connection flow. The downstream breach and inflow channel at Above Brennan showed no change in elevation. Although current peak flow recommendations of 18,600 cfs would be sufficient for connection at all of the priority wetlands surveyed, redesign of levee breaches or periodic removal of deposited sand and debris, especially after large floods, may be necessary to maintain these connections over the long term. The findings of this study confirm the need for periodic assessment of floodplain wetland connections especially after unusually high flows.

The annual and periodic monitoring described above is considered high priority in the Green River, but medium priority in the Gunnison and Colorado Rivers because of the relative use of these areas by razorback suckers and because much of the floodplain has been impacted by gravel mining operations. Estimated periodic costs in each location would be approximately $35,000 per survey effort. Such surveys would be conducted only following peak flows in moderately wet or wet years.

CHANNEL NARROWING

Channel narrowing is a process that can occur in response to changes in the magnitude, duration, frequency, and timing of peak flows, and typically occurs in response to water withdrawals and transfers, regulation of flows by upstream dams, and climate change. The reduction in annual peak flows and reduced frequency of exceeding normal predevelopment bankfull flow creates a cycle of vegetation encroachment of banks, vertical accretion of sediment

[2] Note that changes in these relationships are related to the process of channel narrowing, which is discussed as a separate topic.

on banks, gradual migration of banks toward the river (narrowing), disconnection of floodplain habitats from the main channel, and greater simplification of in-channel habitats. Preventing channel narrowing ensures a more dynamic suite of in-channel and floodplain habitats.

The hypothesis to be tested for channel narrowing is:

H_2: Peak flow magnitude, duration, frequency, and timing affect channel width in the Green, Gunnison, and Colorado Rivers.

Channel narrowing has been evaluated in the Green (Andrews 1986; Lyons et al. 1992; Allred and Schmidt 1999; Orchard and Schmidt 2000), Gunnison (Pitlick et al. 1999), and Colorado Rivers (Van Steeter and Pitlick 1998). In addition, there is an existing study, funded by the National Park Service, to evaluate channel narrowing in Dinosaur National Monument and Canyonlands National Park. The topic of channel narrowing in the Green River was addressed in the larval trigger study plan as there was some concern that shifting the timing of peak flows to coincide with the appearance of razorback sucker larvae could result in lower magnitude peak flows because annual peak releases from Flaming Gorge Dam would no longer be synchronized with peak flows in the Yampa River (Larval Trigger Study Plan Ad Hoc Committee 2012). These information needs were addressed in the larval trigger study plan under the hypothesis "*Channel width and complexity are not affected by the use of a larval trigger*."

Study reaches (e.g., 50 km lengths) should be established in the middle Green (high priority), lower Green (medium priority), lower Gunnison (high priority), middle Colorado (downstream of Gunnison confluence; (medium priority), and lower Colorado (upstream of Green River confluence (medium priority). Changes in channel width, plant density, plant communities, and other habitat characteristics observable in aerial imagery could be used to determine if the flow regime is adequate to prevent vegetation encroachment, channel narrowing, and simplification. In addition, an assessment of channel narrowing and incision/aggradation of the channel may be possible using existing data sets available from USGS streamflow measurements and cross-section geometry near USGS streamflow gages. This analysis could be combined with an assessment of channel response to observed high flows to evaluate channel response to peak flow magnitudes and durations. These recommendations are consistent with, but build on, the recommendations of the Larval Trigger Study Plan Ad Hoc Committee (2012).

Because of the importance of channel narrowing as an indicator of the adequacy of a peak flow regime to maintain suitable habitat conditions and functions, we recommend that narrowing be periodically assessed (e.g., every 5 to 10 years) in all three rivers. This can be done using readily obtainable high-resolution satellite imagery that is available at relatively low cost (about $15,000 per study reach) or aerial imagery (about $50,000 per study reach).

SPAWNING HABITAT AND OTHER GRAVEL AND COBBLE-BED BENTHIC HABITATS

Spawning habitats of the endangered fishes in the Upper Basin are located in a number of locations in the Green, Gunnison, and Colorado Rivers that have the appropriate hydraulic

conditions (riffle) and substrate (gravel and cobble) for egg incubation and early development. These habitats must be well-aerated and relatively clean (i.e., free of fine sediments and submerged vegetation). Other gravel and cobble-bed benthic habitats also are considered here because of their relative importance for maintaining primary and secondary productivity in the wider river ecosystem, and the comparable forces that maintain those habitats. Table 3 presents the reaches identified in LaGory et al. (2003) where understanding the role of peak flows on spawning habitats was considered a primary information need.

The hypotheses to be tested for spawning and other gravel and cobble-bed benthic habitats are:

H_3: Peak flow magnitude, duration, frequency, and timing affect the suitability of spawning habitats in the Green, Gunnison, and Colorado Rivers.

H_4: Peak flow magnitude, duration, frequency, and timing affect productivity of gravel and cobble-bed benthic habitats in the Green, Gunnison, and Colorado Rivers.

Maintenance of suitable conditions in spawning and other gravel and cobble-bed benthic habitats require peak flows of an appropriate magnitude, duration, frequency, and timing to maintain fine sediment in an equilibrium condition (i.e., inputs to and outputs from the reach are approximately equal over a sequence of years), and sufficient to periodically initiate and sustain motion of the bed. The razorback spawning bar in the Green River upstream of the Ashley Creek confluence was studied by Williams et al. (2012; project 85f). Their study identified the sometimes complex nature of these habitats and the effects of hydraulics on sediment transport. At this site, fine sediment transport was observed to increase with increasing flow, but only to a point (around 14,000 cfs) at which net deposition began to occur. This study is considered sufficient to resolve uncertainties identified in LaGory (2003) related to this particular bar; evaluating other gravel and cobble-bed portions of the Green River are considered lower (medium) priority.

Gunnison River flow recommendations (McAda 2003) were based on flows identified by Pitlick et al. (1999) as needed to initiate initial and significant motion of the bed in the lower 100 km of the river. Results presented in Williams et al. (2012) appeared to support different peak flows needed to accomplish the same functions. Although these results were in the range of values presented in Pitlick et al. (1999), field studies of bed load transport may be needed to resolve these differences if considered sufficiently large to affect peak flow recommendations (Pitlick 2011).

We believe that resolving peak flow needs related to the maintenance of spawning areas and other gravel and cobble-bed benthic habitats is of greatest importance in the Gunnison and Colorado Rivers. These rivers have a greater proportion of these substrates than the Green River. Peak flow recommendations for these two rivers (McAda 2003) were largely based on the flows needed to maintain these habitats and, as mentioned in the previous paragraph, there remains some uncertainty of the appropriate magnitude, duration, frequency, and timing of peak flows needed.

An appropriate approach may consist of direct measurements of bed load transport over a series of annual peak flows (e.g., 3-5 peak flows representing a range thought to include initial and significant motion thresholds) coupled with hydrophone measurements for calibration (Graham Matthews & Associates 2011; San Joaquin River Restoration Program 2013). Once calibrated, and considered sufficiently accurate for study purposes, hydrophones alone could be used for peak flow monitoring in later years to determine the frequency, duration, and timing of achieving bed load transport. At least 3 study reaches should be chosen in both the Gunnison and Colorado Rivers. These reaches should be chosen based on the occurrence of important habitats and features. Estimated annual cost for direct measurements of bed load transport is approximately $35,000 per study reach. Estimated annual cost for hydrophone measurements is approximately $12,000.

Although this rigorous approach would provide quantitative estimates of the relationships between flows and bed load transport, a relatively simple approach using uncalibrated hydrophones (to determine the onset of bed mobilization), painted, or RFID-tagged cobbles placed in study areas could confirm years in which peak flows were sufficient for initiating bed load transport. This simpler and less costly approach could be used as an alternate way of monitoring bed load transport during peak flows. Estimated annual cost for measurements using painted or RFID-tagged cobbles is about $8,000.

The Recovery Program should consider resuming benthic substrate monitoring (Lamarra 1999; Osmundson et al. 2002) using depth-to-embeddedness measures to determine the biological health of cobble bars in study reaches of the lower Gunnison River, and Palisade to Loma reach of the middle Colorado River. This monitoring could overlap with the bed load transport study described in the previous paragraph to correlate bed load transport with the depth-to-embeddedness metric. Estimated annual cost for depth-to-embeddedness measurements is about $8,000.

An important component of any study of spawning and other gravel and cobble-bed benthic habitats will be regular monitoring of suspended sediment transport into and out of study reaches because this will determine to a large extent the frequency with which bed load transport would be needed to clear fine sediment from these habitats. Continuous acoustic suspended sediment gages are being deployed by the USGS (Grand Canyon Monitoring and Research Center) in different locations within the Colorado River Basin (Griffiths et al. 2012). Five acoustic gages either have been or will soon be installed in and near Dinosaur National Monument in the Green and Yampa Rivers; see http://www.gcmrc.gov/discharge_qw_sediment/stations/DINO); another acoustic gage is planned for installation on the lower Green River near Mineral Bottom (D. Topping, pers. comm.). Deployment of such gages at the upper and lower ends of the Gunnison River study reach (e.g., associated with the USGS stream gages near Delta [USGS 09144250] and Whitewater [USGS 09152500]) and the Colorado River study reach (e.g., associated with the USGS stream gages near Cameo [USGS 09095500] and the Colorado-Utah state line [USGS 09163500]) would help determine fine sediment balance in important portions of these two rivers. Estimated cost for deploying and operating a suspended sediment transport gage at existing stream gage sites is $35,000 per gage for initial deployment and $20,000 per year for operations and maintenance.

CONNECTED BACKWATER HABITATS

Connected backwaters are low-velocity, channel margin habitats of sand-bedded rivers that form on the shoreward side of sandbars and are connected to the main channel at base flow. Backwater habitats provide important nursery areas for Colorado pikeminnow because they are warmer and typically more productive than nearby main channel habitats. Connected backwaters are common features of sand-bedded portions of the middle and lower Green and middle and lower Colorado Rivers; these habitats are not common in the Gunnison River. Table 3 presents the reaches identified in LaGory et al. (2003) where understanding the role of peak flows and sediment availability on connected backwaters was considered a primary information need.

The hypothesis to be tested for connected backwaters is:

H_5: The effect of peak flow magnitude, duration, frequency, and timing on suspended sediment transport and fine sediment mass balance affect the abundance and characteristics of connected backwater habitats in the Green and Colorado Rivers.

Annual peak and intervening flows rework existing bars and reshape backwaters creating extremely dynamic habitats that vary considerably from year to year. Although an uncertainty was identified in the Flaming Gorge flow recommendations report (Muth et al. 2000) and the geomorphology priorities report (LaGory 2003) regarding the role of peak flow magnitude, duration, frequency, and timing on formation and maintenance of these habitats, studies conducted to date (LaGory et al. 2009) have not identified a clear relationship to flow alone. Although peak flow characteristics are undoubtedly important, fine sediment mass balance is also a dominant factor and should be evaluated. The backwater synthesis currently under development should provide insight into the role of peak flows on connected backwaters in the middle Green River.

Sediment transport and availability of backwater nursery habitats in the Green River was identified as a study topic in the larval trigger study plan (Larval Trigger Study Plan Ad Hoc Committee 2012). That study plan identified a number of studies that would complement those described here including the ongoing Argonne/Western backwater topography study and studies of pikeminnow abundance in backwaters (existing project 138). In addition, the larval trigger study plan identified a need for evaluating sediment transport in the middle Green River.

As described above for the evaluation of benthic habitats in the Gunnison and Colorado Rivers, deployment of USGS acoustic sediment monitoring gages upstream and downstream of critical reaches in the Green and Colorado Rivers would be a good way to monitor fine sediment movement through the system and fine sediment mass balance.

A network of acoustic sediment gages in the Green River could consist of four gages to evaluate sediment transport in the middle Green and lower Green Rivers:

(1) near the existing Jensen, Utah, stream gage (USGS 09261000);

(2) near the existing Ouray, Utah, stream gage (USGS 09272400);

(3) near the existing Green River, Utah, stream gage (USGS 09315000); and

(4) in the lower Green River (e.g., near Mineral Bottom).

Acoustic sediment gages at the Jensen and Mineral Bottom site have been recently deployed (D. Topping, pers. comm.).

A network of acoustic sediment gages in the Colorado River could consist of three gages to evaluate sediment transport in the middle Colorado River:

(1) near the existing Cameo (USGS 09095500) or Palisade, Colorado, stream gages (USGS 09106150);

(2) near the existing Colorado-Utah state line stream gage (USGS 09163500);

(3) near the existing Cisco, Utah, stream gage (USGS 09180500).

The first two gages mentioned were identified as important for evaluating the relationship of peak flows on benthic habitats.

Monitoring of suspended sediment transport and fine sediment mass balance is considered a high priority in the middle Green River and a medium priority in the lower Green and middle and lower Colorado Rivers. These differences relate to the importance of reaches for meeting the needs of endangered fishes as well as the relative influence of upstream dams on flows in those reaches. Estimated cost for deploying and operating a suspended sediment transport gage at existing stream gage sites is $35,000 per gage for initial deployment and $20,000 per year for operations and maintenance.

3 RESEARCH PRIORITIES AND IMPLEMENTATION

As described in Section 2, four habitat-related topics are included in this study plan: (1) floodplain wetland connection to the main channel; (2) channel narrowing; (3) spawning and other gravel and cobble-bed benthic habitats; and (4) connected backwaters. All of these topics are considered high priority and necessary for establishing scientifically based peak flow recommendations. However, priorities do vary among rivers and reaches within those rivers. The priorities set in this study plan draw from, but are not identical to, previously identified priorities in the Green River (Green River Study Plan Ad Hoc Committee 2007) and Gunnison and Colorado Rivers (Aspinall Study Plan Ad Hoc Committee 2011), as well as the geomorphology research priorities report for the Upper Basin (LaGory et al. 2003). It is important to note that the priorities assigned to topics in this study plan are relative to their importance to resolving peak flow uncertainties and not to overall priorities of the Recovery Program. Studies identified as lower priority here could be high priority for other Program elements.

Table 4 summarizes hypotheses, variables to be measured, related studies, and priorities for each topic addressed in the study plan. Overall priorities are categorized as either high or medium (none were identified as low although some rivers and reaches are not included for study) based on the perceived importance of the variable and reach under consideration to the

species most dependent on the habitats, the role of peak flows in habitat maintenance and function, and the importance of the information in understanding that relationship and testing specific hypotheses.

Within topics, certain hypotheses and variables are considered higher priority than others (Table 4). For floodplain wetland connections, understanding the peak flows needed to connect priority floodplain wetlands in the Green River is considered a high priority whereas the same information in the Gunnison and Colorado Rivers is considered medium priority. This difference relates to differences among the rivers in the importance of floodplains to overall razorback sucker populations in the Upper Basin. For channel narrowing, determining changes in channel width through time as a function of peak flow magnitude, duration, frequency, and timing is considered a high priority in the middle Green, lower Gunnison, and middle Colorado Rivers, but a medium priority in the lower Green and lower Colorado Rivers. These differences related to the overall importance of these reaches to endangered fishes in the Upper Basin and the relative influence of dam operations as related to distance downstream. For spawning and other gravel and cobble-bed benthic habitats, obtaining information on bed load and suspended sediment transport was considered a high priority in the lower Gunnison River and middle Colorado River, but a medium priority in the lower Colorado and lower Green Rivers. A previous study (85f) was considered sufficient to address this information need in the middle Green River. Collecting information on suspended sediment transport and fine sediment mass balance was considered a high priority in the middle Green River and a medium priority in the middle Colorado River. These differences relate to the importance of reaches for meeting the needs of endangered fishes as well as the relative influence of upstream dams on flows in those reaches.

The study plan presented here emphasizes the need for monitoring changes in habitats and critical flow and sediment variables through time. Some of the suggested monitoring is continuous or annual (e.g., flow and suspended sediment) whereas others would be less frequent (e.g., channel narrowing every 5 years; surveys of levee breaches and inflow channels of floodplain wetlands following unusually high peak flows). In addition to monitoring, a targeted study to estimate bed load transport in the Gunnison and Colorado Rivers over a series of years with follow-on monitoring of bed load transport using hydrophones (calibrated or uncalibrated) is recommended.

We recognize the possibility that funding limitations could result in an inability to perform all of the studies described here. Wherever possible, we identify existing studies that would serve the same need or that could be modified to address some of the information needs identified in this study plan. In some cases there is considerable overlap between the studies proposed here and in other recent study plans (e.g., the larval trigger study plan). In one case, we identify a more costly but rigorous approach (direct measurement of bed-load transport), but present a low-cost alternative approach (painted or RFID-tagged cobbles). Commonalities with other study plans, alternative approaches, and identified priorities should be considered when developing a cost-effective plan.

The specific objectives, tasks, and expected outcomes for individual studies developed under this plan will be identified in statements of work approved by the Recovery Program.

These projects and the resulting project reports will go through the standard Recovery Program review protocols. It is anticipated that in addition to an annual review of the data collected, a synthesis report will be developed after the first 5 years of the study that summarizes results from individual projects, integrates results, summarizes conclusions, and makes recommendations for future management of peak flows in the Upper Basin. As for any study plan, additional knowledge will be gained during implementation, and it will be important to have enough flexibility to adjust studies and overall approaches in response to this new information. Toward this end, the results of studies will be evaluated each year to determine the need for modification.

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APPENDIX

ESTIMATED COSTS OF NEW PROJECTS IDENTIFIED IN THE PEAK FLOW STUDY PLAN

TABLE A1. Estimated Costs of New Projects Identified In the Peak Flow Study Plan

Topic/Project Activity	Reach and Priority	Start-up or Periodic Cost	O&M Cost	Comments
Floodplain Wetland Connection to the Main Channel				
Field observations to determine flows needed to connect priority floodplain	Middle Green River (Split Mountain to Desolation Canyon), High priority	$35,000/ survey	NA	Conducted most recently after 2011 peak flows. Should be re-evaluated after high flows (e.g. >20,300cfs @ Jensen gage). Monitored, in part, under Larval Trigger Studies (Project Nos. 164, 165 22f).
Field observations to determine flows needed to connect priority floodplain wetlands in the Colorado River	Gunnison (Hartland Dam to Roubideau Creek) and Colorado (Palisade to Loma) Rivers, Medium priority	$35,000/ survey	NA	
Channel Narrowing				
Evaluate aerial imagery of study reaches or an analyze cross-section information near USGS streamflow gages.	Middle Green River (Split Mountain to Desolation Canyon); Lower Gunnison River (Hartland to Colorado River); Middle Colorado River (Gunnison River to Loma), High	$15,000 to $50,000/ study reach	NA	Should be re-evaluated every 5-10 yrs. Use of satellite images is the less expensive approach.
	Lower Green River (Gray Canyon to Colorado River), Lower Colorado River (Loma to Green River), Medium priority	$15,000 to $50,000/study reach	NA	
Spawning and Benthic Habitats				
Evaluate bed load transport, fine sediment mass balance, and depth to embeddedness in gravel and cobble-bed portions of the	Lower Gunnison River (Hartland Dam to Colorado River), Middle Colorado River (Palisade to Loma), High priority			Project 85f resolved uncertainties related to a critical Green River spawning bar in the Split Mountain to Desolation Canyon reach
	Lower Colorado River (Loma to Green River), Lower Green River (Desolation and Gray Canyons), Medium priority			
Option 1 - Measure Bedload Transport		$35,000/ survey site/ yr	NA	Data would need to be gathered over a range of hydrologies. Bed load estimate reflect 4-8 visits/yr and USGS estimates that there would be a considerable cost savings if multiple sites were chosen, e.g., $110,000/yr for 5-6 survey sites.

Table A1 (Cont.)

Topic/Project Activity	Reach and Priority	Start-up or Periodic Cost	O&M Cost	Comments
Option 2 - Hydrophone Measurement of Bedload Transport		$12,000/ survey site/ yr	NA	
Option 3 - Depth to Embeddedness		$8,000 survey site/ yr	NA	
Option 4 - Painted or RFID tagged cobbles.		$8,000 survey site/ yr	NA	
Connected Backwater Habitats				
Establish network of suspended sediment transport and fine sediment mass balance monitoring stations in critical reaches. Tiers off USGS- GCMRC approach.	Middle Green River (Split Mountain Canyon to Desolation Canyon), High priority			Existing backwater synthesis project will summarize existing information. Some cost share available for sediment monitoring at Jensen site. All other sites represent full start-up and O&M costs. Priority is based on proximity to known Colorado pikeminnow nursery areas. GCMRC, NPS, and PDO are exploring funding sources outside the Recovery Program.
	Jensen gage	$35,000	$10,000	
	Ouray gage	$35,000	$20,000	
	Lower Green River (Swasey to Colorado River), Medium priority			
	Near Green River, UT gage	$35,000	$20,000	
	Mineral Bottom	$35,000	$20,000	
	Colorado (Cameo to Green River confluence), Medium priority			
	Near Cameo gage, Medium priority	$35,000	$20,000	
	Near CO / UT Stateline gage, High priority	$35,000	$20,000	
	Near Potash, High priority	$35,000	$20,000	
	Lower Gunnison River (Hartland Dam to Colorado River), Low priority			
	Near Delta	$20,000	$20,000	
	Near Grand Junction gage	$20,000	$20,000	