A STRATEGY TO EVALUATE PEAK FLOW RECOMMENDATIONS FOR SEDIMENT TRANSPORT AND HABITAT MAINTENANCE IN THE UPPER COLORADO RIVER BASIN

A TECHNICAL SUPPLEMENT TO THE GREEN RIVER AND ASPINALL STUDY PLANS

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August 2015

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ACKNOWLEDGMENTS

This report was developed based on a review of existing studies and information as well as discussions with a group of geomorphologists, biologists, and hydrologists convened by the Upper Colorado River Endangered Fish Recovery Program. This group included scientists and experts from Reclamation (Blair Greimann), U.S. Geological Survey (Paul Grams, J. Toby Minear, David Topping, and Cory Williams), University of Colorado-Boulder (John Pitlick), Utah State University (Jack Schmidt), water users (Tom Pitts), and environmental interests (Dan F. Luecke). While these discussions were important in shaping this report, the findings and recommendations reported here are those of the authors.

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. The Upper Colorado River Endangered Fish Recovery Program (Recovery Program) has developed flow recommendations for most river reaches to assist in the recovery of those species. The Recovery Program also developed study plans for the Green River (Green River Study Plan Ad Hoc Committee 2007) and Gunnison and Colorado Rivers (Aspinall Unit Study Plan Ad Hoc Committee 2011) to evaluate those flow recommendations.

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 a need to assess, prioritize, and identify remaining information needs to resolve uncertainties, monitor effects of recommended flows, and provide a strong scientific basis for peak flow recommendations and legal protection of the flows needed to support the recovery of Colorado River fishes. This Peak Flow Technical Supplement (Technical Supplement) identifies study approaches and techniques to evaluate remaining uncertainties associated with the Recovery Program's peak flow recommendations. It is intended to supplement the existing Study Plans mentioned above.

This Technical Supplement was developed based on a review of existing studies and information as well as discussions with a group of geomorphologists, biologists, and hydrologists convened by the Recovery Program. This group included scientists and experts from Reclamation, U.S. Geological Survey, University of Colorado-Boulder, Utah State University, U.S. Fish and Wildlife Service, Argonne National Laboratory, water users, and environmental interests. The group (1) reviewed previously identified uncertainties, and research that has been conducted to date to resolve these uncertainties in the basin, and (2) discussed current research techniques that could be applied to resolving remaining uncertainties. This information was used

by the Technical Supplement authors to develop a range of options to monitor peak flow-related effects and address remaining uncertainties.

The Technical Supplement proposes a targeted monitoring and research strategy to address five topics related to the role of peak flows in building and maintaining important fish habitats: (1) peak flows needed to connect floodplain wetlands to the main channel; (2) peak flows needed to maintain spawning habitats and other gravel and cobble-bed benthic habitats; (3) peak flows needed to build and maintain connected backwater habitats; (4) peak flows needed to prevent channel narrowing; and (5) peak flows needed to maintain the mass balance of fine sediment. The last two topics were not explicitly identified in the Green River or Aspinall Study Plans, but represent systemwide effects of peak flows that are critically important for maintaining channel complexity and both inchannel and floodplain habitats. All of these topics are considered high priority in one or more of the rivers in the Upper Basin, and addressing them would bolster scientifically based peak flow recommendations. However, priorities do vary among rivers and reaches within those rivers.

In developing this Technical Supplement, the authors reviewed ongoing monitoring associated with existing study plans, and, where considered appropriate, makes recommendations for periodic or short-term focused research designed to address information gaps associated with these five effects. This Technical Supplement, together with the two Study Plans, is intended to provide the scientific basis for peak flow requirements, and legal protection of the flows needed to support the recovery of Colorado River Basin fishes. The following studies and monitoring are recommended to address high priority information needs for consideration by the Program:

Topic 1: Floodplain Wetland Connection to the Main Channel

1. Green River (between Yampa and White Rivers): Continued periodic surveys of levee breaches and associated connection channels similar to those conducted in 2012 and 2014 following high-magnitude peak flows (e.g., > 20,000 cfs) to ensure continued connection in average years.

2. Green River (between Yampa and White Rivers): New surveys of lower elevation downstream levee breaches and associated connection channels following lower magnitude peak flows that normally connect these channels (e.g., 12,000 to 15,000 cfs).

Topic 2: Spawning Habitat and Other Gravel and Cobble-Bed Benthic Habitats

3. Gunnison River (Harland Dam to Colorado River): New study needed to evaluate bed-load transport in gravel and cobble-bed portions of the Gunnison River

Topic 3: Connected Backwater Habitats

4. Green River (between Yampa and White Rivers): Periodic monitoring of the surface area and number of backwater habitats in the Green River using aerial or satellite imagery

Topic 4: Channel Narrowing

5. Green River (between Yampa and White Rivers): Periodic monitoring of future channel narrowing and comparison to historic rates using aerial or satellite imagery

6. Gunnison River (Hartland Dam to Colorado River): Periodic monitoring of future channel narrowing and comparison to historic rates using aerial or satellite imagery

7. Colorado River (downstream of Gunnison River): Periodic monitoring of future channel narrowing and comparison to historic rates using aerial or satellite imagery

Topic 5: Fine Sediment Mass Balance

8. Green River (at Jensen and Ouray gages): Monitor sediment balance in the middle Green River

9. Gunnison River (at Delta and Whitewater gages): Monitor sediment balance in the Gunnison River downstream of Hartland Dam

10. Colorado River (at Cameo and State Line gages): Monitor sediment balance in the Colorado River above and below the confluence with the Gunnison River

The specific objectives, tasks, and expected outcomes for individual studies developed from this Technical Supplement will need to 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 information gathered from studies identified in this Technical Supplement would contribute to ongoing evaluations of the Recovery Program flow recommendations as characterized in the Green River and Aspinall Study Plans. Formal evaluation of all aspects of the flow recommendations, including the peak flow components, will follow the schedules identified in those Study Plans.

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. 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. 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.

In evaluating geomorphology research priorities, LaGory et al. (2003) identified reaches of the Green, Gunnison, and upper Colorado River on the basis of the dominant geomorphic planform (Table 1). Three planforms were considered: (1) restricted meander, (2) fixed meander, and (3) canyon. These planforms describe various levels of confinement of the river channel within the surrounding geology, which in turn affects habitat characteristics relevant to endangered fishes. Restricted meanders occur in broad alluvial terraces that are bounded by relatively more resistant geology. Valleys in which restricted meanders occur are relatively wide, and only the outside bends are in contact with bedrock. Fixed meanders are confined by resistant geology on both outside and inside bends of the main channel and result from symmetrical incision associated with rapid down-cutting through the geologic formation. Canyons consist of relatively straight sections of river with resistant geology on both sides of the river.

These planforms affect the distribution and characteristics of important fish habitats. Spawning habitats occur in canyon or fixed meanders where the substrate is dominated by gravels and cobbles. Floodplain wetland nursery habitats and connected backwater nursery habitats occur in restricted meanders where sand is the dominant substrate.

Floodplain wetland habitats occur on high-elevation alluvial terraces that must be maintained by relatively high peak flows and connected by peak flows at a sufficient frequency to meet the life history needs of the razorback sucker and other fishes using them. Peak flows form and reshape the sandbars that protect connected backwater habitats from the higher velocity, colder main channel. Peak flows play different roles in these different environments, but in all, preventing channel narrowing and maintaining a sand mass balance that is in equilibrium ensures the maintenance of a dynamic channel, which is important for the long-term maintenance of high-quality habitats.

TABLE 1. Location and Dominant Planforms of River Reaches of the Upper Colorado River Basin

	River Reach[a]	River Km[b]	River Mi[b]	Dominant Planform
I. Green River Subbasin				
Green River Mainstem				
1	Flaming Gorge Dam to Browns Park	637–660	396–410	Canyon
2	Browns Park	583–637	362–396	Restricted meander
3	Lodore Canyon	551–583	342–362	Canyon
4	Yampa River to Island Park	538–551	334–342	Canyon
5	Island and Rainbow Parks	526–538	326–334	Restricted meander
6	Split Mountain Canyon	514–526	319–326	Canyon
7	Split Mountain Canyon to Desolation Canyon	348–514	216–319	Restricted meander
8	Desolation and Gray Canyons	212–348	132–216	Canyon
9	Gray Canyon to Labyrinth Canyon	148–212	92–132	Restricted meander
10	Labyrinth and Stillwater Canyons	0–148	0–92	Fixed meander
Green River Tributaries				
11	Yampa River–Above Yampa Canyon	72–208	45–129	Restricted meander
12	Yampa River–Yampa Canyon	0–72	0–45	Canyon
	Little Snake River	–	–	Restricted meander
	Duchesne River	–	–	Restricted meander
	White River	–	–	Restricted meander
	Price River	–	–	Fixed meander
	San Rafael River	–	–	Restricted meander
II. Upper Colorado River Subbasin				
Colorado River Mainstem				
1	Rulison to DeBeque Canyon	328–373	204–232	Restricted meander
2	DeBeque Canyon to Palisade	298–328	185–204	Fixed meander
3	Palisade to Gunnison River	275–298	171–185	Restricted meander
4	Gunnison River to Loma	248–275	154–171	Restricted meander
5	Loma to Westwater Canyon	201–248	125–154	Fixed meander[c]
6	Westwater Canyon	182–201	113–125	Canyon
7	Cottonwood Wash to Dewey Bridge	151–182	94–113	Restricted meander
8	Dewey Bridge to Hittle Bottom	142–151	88–94	Fixed meander
9	Hittle Bottom to White Rapid	126–142	78–88	Restricted meander
10	White Rapid to Jackass Canyon	113–126	70–78	Fixed meander
11	Jackass Canyon to Moab Bridge	103–113	64–70	Fixed meander
12	Moab Bridge to Green River	0-103	0-64	Fixed meander
13	Green River to Lake Powell	-23–0	-14–0	Canyon
Colorado River Tributaries				
14	Gunnison River–Hartland Dam to Roubideau Cr.	94–107	58–66	Restricted meander
15	Gunnison River–Roubideau Cr. to Colorado River	0–94	0–58	Fixed meander
	Dolores River	–	–	Fixed meander

[a] Reaches identified in LaGory et al. (2003).

[b] River kilometer and river mile represent distance from river mouth as follows: Green River, distance upstream of Colorado River; Yampa River, distance upstream of Green River; Colorado River, distance upstream of Green River; Gunnison River, distance upstream of Colorado River. "–" indicates entire tributary considered.

[c] The Loma to Westwater Canyon reach includes Black Rocks, a 1.5-mi (2.4-km) canyon.

Source: LaGory et al. 2003

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 a need to assess, prioritize, and identify remaining information needs to resolve uncertainties, and provide a strong scientific basis for peak flow requirements and their legal protection. The recommendations for studies and monitoring in this Technical Supplement, together with the two Study Plans and ongoing monitoring, are intended to provide guidance for strengthening the scientific basis for peak flow recommendations and legal protection of the flows needed to support the recovery of Colorado River fishes. The Technical Supplement offers a number of study approaches and techniques to obtain remaining information needs. It is intended to supplement the existing Green River and Aspinall Study Plans mentioned above.

2 METHODS

The recommendations in this Technical Supplement were developed based on the authors' review of existing studies and information as well as discussions with a group of geomorphologists, biologists, and hydrologists convened by the Recovery Program. This group included scientists and experts from Reclamation, U.S. Geological Survey (USGS), University of Colorado-Boulder, Utah State University, U.S. Fish and Wildlife Service (USFWS), Argonne National Laboratory (Argonne), water users, and environmental interests. Development of the Technical Supplement was coordinated by the Recovery Program. The group (1) reviewed previously identified uncertainties, and research that has been conducted to date to resolve those uncertainties in the basin, and (2) discussed current research techniques that could be applied to resolving remaining uncertainties. This information was used by the Technical Supplement authors to develop a range of options to monitor peak flow-related effects and address remaining uncertainties.

The anticipated effects, uncertainties, and priorities identified in the Green River Study Plan, Gunnison and Colorado River Study Plan, and Geomorphology Research Priorities Report are presented in Tables 2, 3, and 4, respectively. As identified in Tables 2-4, there are differences in the priorities assigned to different peak flow-related topics, and in different rivers and reaches. The assigned priorities were 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. We reexamined priorities based on current knowledge and research conducted since the Study Plans were developed and implemented.

TABLE 2 Green River Study Plan—High Priority Anticipated Physical Effects and Uncertainties Associated with Recommended Peak Flows

High Priority Anticipated Effects[a]	High Priority Uncertainties
Spring Peak (Reach 2)	
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.	The area of terrace and depression floodplains inundated at different flows. Flow and stage at which floodplains with levee breaches become sufficiently inundated (area, depth, volume) to provide nursery habitat for razorback suckers. Area, depth, volume, and persistence of floodplain depression habitat after peak flows recede and the relationship, if any, between these and the magnitude of the peak flow. 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.
Summer Through Winter Base Flows (Reach 2)	
Base flows in summer and autumn scaled to the hydrologic condition favor the formation of backwaters and other low-velocity shoreline nursery habitats.	The effect of peak flows, sediment availability, and antecedent conditions on the relationship between base flow level and backwater habitat availability.

[a] Uncertainties associated with Reach 1 and 2 were identified as Low or Medium Priority.

Source: Green River Study Plan Ad Hoc Committee 2007

TABLE 3 Gunnison and Colorado Rivers Study Plan—High Priority Anticipated Physical Effects and Uncertainties Associated with Recommended Peak Flows

High Priority Anticipated Effects	High Priority Uncertainties
Spring Flows Are Necessary to Maintain Channel under Various Hydrologic Conditions (Gunnison River)[(a)]	
Wet and Moderately Wet: The median level for significant motion is reached or exceeded in the river, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in large areas of the river. Gravel is flushed from pools, creating critical wintering habitat for both species. Widespread areas with clean substrates should provide habitat needed for maximum reproductive success of Colorado pikeminnow and increased primary and secondary production.	Relationship between fine sediments and primary and secondary production. Periodic, channel wide flushing of cobble bars is necessary to maintain habitat; however, the frequency required is unknown. Frequency (recurrence interval) and duration (number of days) that flows need to exceed half bankfull and bankfull discharge to maintain the suite of habitats required by the endangered fishes.
Average Wet: The median level for significant motion is reached or exceeded in the river. Widespread cleansing of gravel and cobble bars is accomplished. In-channel habitats used by endangered fish will be maintained in important river reaches; channel narrowing will be slowed or prevented.	Amount and quality of habitat necessary to maintain populations at levels identified in recovery goals for the four species.
Average: The median level for initial motion will be reached, providing some cleansing of gravel and cobble bars. This will prepare spawning habitat for Colorado pikeminnow and increase primary and secondary production.	
Moderately Dry: In-channel maintenance will not occur unless initial motion is reached for at least one day; however, fine material on the surface will be moved and further deposition will be slowed.	
Dry: No in-channel scouring of gravel or cobble bars is anticipated at this flow; however, fine material on the surface will be moved and further deposition will be slowed.	

Table 3 (Cont.)

High Priority Anticipated Effects	High Priority Uncertainties
Spring Flows Provide Floodplain Habitat Under Various Hydrologic Conditions (Colorado River)[(b)]	
Wet and Moderately Wet: Floodplain habitats will be extensive, but the surface area of those habitats is not quantified. The duration of flows greater than 35,000 cfs will ensure that floodplain area is available to improve growth and survival of YOY razorback suckers. The duration of flows exceeding significant motion will ensure that YOY razorback sucker will be able to utilize floodplain habitats for sufficient time to increase their growth and survival. Average Wet: Flooding in and around Walker SWA will provide important floodplain habitats, but the extent of available habitat is not known. 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. Average Dry and Moderately Dry: 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. Dry: No flooded bottomland habitat will be provided, but some inundation of tributary mouths may occur.	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.

[(a)] Uncertainties identified with floodplain habitats in the Gunnison River were identified as Medium Priority.

[(b)] Uncertainties associated with channel maintenance in the Colorado River were identified as Medium Priority.

Source: Aspinall Study Plan Ad Hoc Committee 2011

TABLE 4 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 (RM 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

Not surprisingly, there was consistency in the high priority research needs identified in these reports. To summarize, the following high priority uncertainties were identified in one or more of the reports:

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).

- Area, depth, volume, and persistence of floodplain depression habitat after peak flows recede and the relationship, if any, between these and the magnitude of the peak flow (Green River).

- 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).

Spawning Bars and Other Gravel and Cobble-Bed Benthic Habitats

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

- 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). 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).

- Amount and quality of habitat necessary to maintain populations at levels identified in recovery goals for the four species (Gunnison River).

Connected Backwater Habitats

- 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).

The authors revisited these priorities in the light of their importance to endangered fishes and the relative influence of upstream dams, and identified a subset of these as high priority. As discussed in Section 1 and presented in Table 1, the location of specific habitats is largely related to channel morphology 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 (restricted meanders) of Upper Basin rivers. Connected backwaters usually form on the shoreward side of sandbars and are found in low-gradient meandering, usually alluvial, sand-bedded river segments (restricted meanders). Inchannel spawning bars are located in higher gradient, gravel and cobble-bed reaches (canyons and fixed meanders). Peak flows perform very different functions in these different reaches and habitats, and the underlying geomorphic processes related to habitat maintenance require different study approaches. These different functions and processes informed the proposed monitoring and research presented in Section 3.

3 RECOMMENDED APPROACH TO ADDRESS PEAK FLOW-RELATEDUNCERTAINTIES AND INFORMATION NEEDS

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 effectiveness of peak flow recommendations in different rivers and reaches is the intent of the monitoring and research recommended in this Technical Supplement.

We propose to supplement the existing Study Plans with a data collection effort that is targeted and focuses on remaining high priority information needs and monitoring of long-term systemwide trends. Five topics related to the role of peak flows in building and maintaining important fish habitats are addressed in this Technical Supplement: (1) peak flows needed to maintain the connection of floodplain wetlands to the main channel; (2) peak flows needed to maintain spawning habitats and other gravel and cobble-bed benthic habitats; (3) peak flows needed to build and maintain connected backwater habitats; (4) peak flows needed to prevent channel narrowing; and (5) peak flows needed to maintain the mass balance of fine sediment in each river. The last two topics were not explicitly identified in the Green River or Aspinall Study Plans, but represent systemwide effects of peak flows that are critically important for maintaining channel complexity and both inchannel and floodplain habitats. All of these topics are considered high priority and addressing them through a targeted research and monitoring program would bolster scientifically based peak flow recommendations. However, priorities vary among river reaches based on the importance of those reaches for life stages of endangered fish. The topics of interest, previous or ongoing related studies, remaining high priority information needs, and recommended studies and monitoring are described here and summarized in Table 5.

It is important to note that the high priority assigned to topics in this Technical Supplement is relative to their importance to resolving peak flow uncertainties and not to their overall priority to the Recovery Program. Wherever possible, the Technical Supplement identifies existing projects that could be modified or expanded to meet information needs in order to capitalize on well-established protocols. Costs for potential new projects are described below and presented in the Appendix.

TABLE 5. Peak Flow Topics, Related and Ongoing Studies, Remaining High Priority Information Needs, and Recommended Studies and Monitoring for the Green, Gunnison, and Colorado Rivers

Topic	River	Related Completed or Ongoing Studies	Remaining High Priority Information Needs	Recommended Studies and Monitoring[1]
1. Floodplain Wetland Connection to the Main Channel				
Peak flow magnitude needed to connect floodplain wetland habitat to main channel	Green (between Yampa and White Rivers)	Studies conducted under the Larval Trigger Study Plan (LTSP Ad Hoc Committee 2012) are addressing uncertainties related to connection of priority floodplains, suitability of inundated floodplain habitats, and the response of native and nonnative fish to experimental use of a larval trigger to determine the timing of high releases from Flaming Gorge Dam.	Determination of remaining information needs awaits completion of studies associated with the Larval Trigger Study Plan.	No new studies are recommended at this time to address this topic.
Maintenance of levee breaches and inflow channels allowing connection with main channel at average or higher peak flows	Green (between Yampa and White Rivers)	Recently completed surveys of levee breaches and inflow channels following high peak flows in 2011 and 2014 (LaGory et al.in prep) evaluated the effects of these flows on sediment deposition and erosion in breaches and floodplain depressions.	Effects of future peak flows on sediment deposition and scouring of floodplain connections.	1. Continued periodic surveys of levee breaches and associated connection channels similar to those conducted in 2012 and 2014 following high-magnitude peak flows (e.g., > 18,000 cfs) to ensure continued connection in average years. 2. New surveys of downstream lower elevation levee breaches and connection channels following lower magnitude peak flows that normally connect these channels (e.g., 12,000 to 15,000 cfs). See Topic 4 “Channel Narrowing” below. See Topic 5 “Fine Sediment Mass Balance” below.

Table 5 (Cont.)

Topic	River	Related Completed or Ongoing Studies	Remaining High Priority Information Needs	Recommended Studies and Monitoring[1]
2. Spawning Habitat and Other Gravel and Cobble-Bed Benthic Habitat				
Peak flow magnitude needed to maintain gravel and cobble-bed habitats	Green (between Yampa and White Rivers)	Williams et al. (2012; Project 85f) evaluated razorback spawning bar in middle Green River	Effects of future flow regimes on fine sediment balance	See Topic 5 “Fine Sediment Mass Balance” below
	Gunnison (Hartland Dam to Colorado River)	Pitlick et al. (1999) assessed bed-load transport at multiple locations in the lower Gunnison River. Williams et al. (2012; Project 85f) assessed flows needed to mobilize bed-load at one site in the Gunnison River.	Flows needed to mobilize bed load in multiple important reaches of the Gunnison River	3. New study to evaluate bed-load transport in gravel and cobble-bed portions of the Gunnison River
			Effect of future flow regimes on fine sediment balance	See Topic 5 “Fine Sediment Mass Balance” below
	Colorado (upstream and downstream of Gunnison River)	Pitlick et al. (1999) assessed bed-load transport at multiple locations in the upper Colorado River.	Effect of future flow regimes on fine sediment balance	See Topic 5 “Fine Sediment Mass Balance” below
3. Connected Backwater Habitats				
Effect of peak flows on backwater characteristics and availability	Green (between Yampa and White Rivers)	Recent backwater synthesis reports (Bestgen and Hill 2014; Grippo et al. 2015; Project FR BW-Synth) summarized existing information on physical and biological relationships.	Effect of future peak flows and flow regimes on backwater habitat availability	4. Periodic monitoring of the surface area and number of backwater habitats in the Green River using aerial or satellite imagery See Topic 4 “Channel Narrowing” below. See Topic 5 “Fine Sediment Mass Balance” below.

Table 5 (Cont.)

Topic	River	Related Completed or Ongoing Studies	Remaining High Priority Information Needs	Recommended Studies and Monitoring[1]
4. Channel Narrowing				
Effect of peak flows on channel narrowing and related habitat characteristics	Green (between Yampa and White Rivers)	Andrews (1986), Lyons et al. (1992), Allred and Schmidt (1999), and Orchard and Schmidt (2000) examined the occurrence of channel narrowing in the middle and lower Green River. The Larval Trigger Study Plan identified channel narrowing as an important topic for study.	Rate and magnitude of channel narrowing	5. Periodic monitoring of future channel narrowing in the Green River and comparison to historic rates using aerial or satellite imagery
	Gunnison (Hartland Dam to Colorado River)	Pitlick et al. (1999) determined rates of channel narrowing in the Gunnison River	Rate and magnitude of channel narrowing	6. Periodic monitoring of future channel narrowing in the Gunnison River and comparison to historic rates using aerial or satellite imagery
	Colorado (downstream of Gunnison River)	Van Steeter and Pitlick (1998) determined rates of channel narrowing in the Colorado River	Rate and magnitude of channel narrowing	7. Periodic monitoring of future channel narrowing in the Colorado River and comparison to historic rates using aerial or satellite imagery
5. Fine Sediment Mass Balance				
Effect of peak flows on fine sediment mass balance	Green (at Jensen and Ouray gages)	Williams et al (2012; Project 85f) evaluated fine sediment transport in the Green River	Effect of future flow regimes on fine sediment balance	8. Monitor sediment balance in the middle Green River
	Gunnison (at Delta and Whitewater gages)	Williams et al (2012; Project 85f) evaluated fine sediment transport in the Gunnison River	Effect of future flow regimes on fine sediment balance	9. Monitor sediment balance in the Gunnison River downstream of Hartland Dam
	Colorado (at Cameo and State Line gages)	Williams et al (2012; Project 85f) evaluated fine sediment transport in the Colorado River	Effect of future flow regimes on fine sediment balance	10. Monitor sediment balance in the Colorado River above and below the confluence with the Gunnison River

3.1 FLOODPLAIN WETLAND CONNECTION TO THE MAIN CHANNEL

Floodplain wetland habitats 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 to meet life history needs. 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.

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. This Technical Supplement, 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.

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). The Larval Trigger Study Plan (LTSP) identified studies related to flow magnitude, duration, frequency, and timing related to connecting priority floodplain 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 LTSP 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 LTSP, 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.[1] As suggested in that plan, a new field study to collect these data could tier from Recovery Program Project C6-Hydro. Similar studies have not been undertaken in the Gunnison and Colorado Rivers, but are considered a lower priority.

To evaluate changes in connection flows after the high peak flows of 2011 and 2014, staff from Western Area Power Administration, Argonne, and USFWS surveyed levee breaches in eight priority wetlands in the middle Green River. They determined that most upstream and some 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 breaches and associated connection channels of two wetlands (Escalante and Old Charley Wash) showed reductions in elevation and subsequent decrease in connection flow. The downstream breach and connection channel at Above Brennan showed no change in elevation. The findings of these studies confirmed the need for periodic assessment of floodplain wetland connections especially after unusually high flows for upstream breaches (e.g., 20,000 cfs) and lower flows (e.g., 12,000-

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

15,000 cfs) for downstream breaches. Any flow higher than the current connecting flow has the potential to fill an inflow channel.

Recommended New Studies Related to Floodplain Wetland Habitats

We recommend periodic topographic surveying of floodplain wetland breaches and connection channels in the middle Green River to determine any changes in the magnitude of peak flows needed to connect priority floodplains to the main channel. This monitoring is needed to ensure these connections are maintained through time, and that breaches and connecting channels do not fill with sediment transported at higher peak flows. Such monitoring is most needed after peak flows that exceed current connection flow magnitudes. For upstream breaches, surveys should be conducted whenever flows exceed approximately 18,000 cfs. For downstream breaches, surveys should be conducted whenever flows exceed approximately 12,000 cfs.

This periodic monitoring is considered high priority in the middle Green River, but lower priority in the Gunnison and Colorado Rivers because of the relatively low use of the Gunnison and Colorado Rivers by razorback suckers, and because much of the floodplain wetland habitats in these two rivers have been impacted by gravel mining operations. Estimated periodic costs would be approximately $35,000 per river survey, and could be discontinued after relationships are established or if engineered modifications to priority wetlands are made to reduce sedimentation effects (e.g., recent changes to Johnson Bottom).

3.2 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 (LaGory et al. 2003). 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 (riffles and runs) are important to endangered fish because these habitats are highly productive especially if kept free of fine sediments.

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 mass balance 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; we consider evaluating other gravel and cobble-bed portions of the Green River lower 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. The approach used by Pitlick et al. (1999) relied on modeled relationships between flow and dimensionless shear stress, rather than direct measurements of bed-load transport during peak flow events. Results presented in Williams et al. (2012; Project 85f) indicated that higher peak flows than presented in Pitlick et al. (1999) were needed to accomplish the same functions, but the findings of Williams et al. (2012) were based on measurements at only one site in the Gunnison River, whereas those of Pitlick et al. (1999) were based on multiple sites that exhibited site-specific variation.

Recommended New Studies Related to Spawning Habitat and Other Gravel and Cobble-Bed Benthic Habitats

Identifying peak flow needs related to the maintenance of spawning areas and other gravel and cobble-bed benthic habitats is considered high priority only in the Gunnison River. The Gunnison River is closer to the influence of an upstream dam (Aspinall Unit) than the upper Colorado River, and has a greater proportion of gravel and cobble substrates than the Green River due to differences in channel morphology. Peak flow recommendations for the Gunnison River (McAda 2003) were largely based on the flows needed to maintain these habitats, as identified in Pitlick et al. (1999), but, as mentioned in the previous paragraph, there remains some uncertainty regarding the appropriate magnitude, duration, frequency, and timing of peak flows needed. Direct measurements of bed-load transport or habitat conditions are needed to resolve these uncertainties.

There are several options for evaluating the peak flow magnitude needed for bed-load transport. Direct measurements can be taken 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 (e.g., Graham Matthews & Associates 2011; San Joaquin River Restoration Program 2013). Once calibrated, and if 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. We recommend that at least 3 study reaches be chosen in the Gunnison River for this study. 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 to estimating bed-load transport 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) or marked cobbles (either painted or RFID-tagged) placed in study areas could identify those years in which peak flows were sufficient for initiating bed-load transport. This simpler and less costly approach could be used instead of monitoring bed-load transport rates during peak flows, but provides only a determination of whether or not the bed was mobilized. Estimated annual cost for measurements using painted or RFID-tagged cobbles is about $8,000.

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 is another approach to looking at the effectiveness of peak flows for maintaining benthic habitats. This monitoring could be conducted on its own or in conjunction with one of the bed-load transport studies described above 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. See a discussion of this topic and recommended studies in Section 3.5.

3.3 CONNECTED BACKWATER HABITATS

Connected backwaters are low-velocity, channel margin habitats of sand-bedded rivers that usually 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.

Annual peak and intervening flows rework existing bars and reshape backwaters creating extremely dynamic habitats that vary considerably from year to year. 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. The backwater synthesis report (Grippo et al. 2015; Project FR BW-Synth), found some support for the hypothesis that higher peak flows result in the need for higher base flows to maximize backwater habitat. That study also identified a trend of decreasing number of backwaters and increasing average size over the time period of 1987 through 2013 that may be related to channel narrowing. Although peak flow characteristics are undoubtedly important, fine sediment mass balance is also an important factor and should be evaluated. Channel narrowing and fine sediment mass balance, and the recommended monitoring studies to examine these topics are discussed in Sections 3.4 and 3.5, respectively.

Sediment transport and availability of backwater nursery habitats in the Green River was identified as a study topic in the LTSP (Larval Trigger Study Plan Ad Hoc Committee 2012). That study plan identified a number of studies including the ongoing Argonne/Western backwater topography study and studies of pikeminnow abundance in backwaters (existing Project 138). Those data sets and long term monitoring of larval Colorado pikeminnow drift were analyzed and presented in the backwater synthesis reports (Bestgen and Hill 2014; Grippo et al. 2015; Project FR BW-Synth). In addition, the LTSP identified a need for evaluating sediment transport in the middle Green River.

Recommended New Studies Related to Connected Backwater Habitats

We recommend periodic monitoring (e.g., every 5 years) of the surface area and number of backwater habitats in the middle Green River using aerial or satellite imagery obtained at base flows to determine the effects of future peak flows and flow regimes on backwater habitat availability. This can be done using readily obtainable high-resolution satellite imagery that is available at relatively low cost (about $15,000) or aerial imagery (about $50,000). Lower, but potentially adequate, resolution images can be obtained from the U.S. Department of Agriculture's National Agriculture Imagery Program (NAIP) free of charge. Availability can be limited, but NAIP imagery is usually collected frequently enough to allow assessment of long-term trends. Similar monitoring in the lower Green River and the Colorado River is considered a lower priority because of their greater distance from upstream dams. Note that this monitoring effort could be coordinated with monitoring of channel narrowing described in Section 3.4 and use the same imagery. These recommendations are consistent with, but build on, the recommendations of the Larval Trigger Study Plan Ad Hoc Committee (2012).

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

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 LTSP 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 LTSP under the hypothesis "*Channel width and complexity are not affected by the use of a larval trigger*."

Recommended New Studies Related to Channel Narrowing

We recommend that channel narrowing be measured in reaches (e.g., 50-km lengths) of the middle Green River, lower Gunnison River (downstream of Hartland Dam), and middle reach of the upper Colorado River (downstream of the Gunnison River confluence). Changes in channel width, plant density, plant communities, and other habitat characteristics observable in aerial imagery should be measured and used to determine if the flow regime is adequate to prevent vegetation encroachment, channel narrowing, and simplification. An assessment of channel narrowing and incision/aggradation of the channel also may be possible using existing data sets available from USGS streamflow measurements and cross-section geometry near USGS streamflow gages.

An analysis of channel narrowing should include an assessment of channel response to very high flows (e.g., > 20,000 cfs in the Green River, > 14,000 cfs in the Gunnison River, and > 35,000 cfs in the Colorado River) to determine the ability of high peak flow magnitudes and durations to reverse previous channel narrowing.

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). NAIP imagery is of lower, but potentially adequate, resolution and is available free of charge. Availability can be limited, but NAIP imagery is usually collected frequently enough to allow assessment of long-term trends. These recommendations are consistent with, but build on, the recommendations of the Larval Trigger Study Plan Ad Hoc Committee (2012).

3.5 FINE SEDIMENT MASS BALANCE

One of the most critical systemwide effects of peak flows relates to the mass balance of fine sediments. Peak flows of sufficient magnitude and duration are needed to ensure sediment input and output to critical reaches is maintained in equilibrium. If such an equilibrium is not maintained over the long term, loss or degradation of suitable habitats, channel narrowing, and channel simplification will occur to the detriment of the river ecosystem and native fish. On this basis, we consider monitoring of fine sediment mass balance as a high priority in the Green, Gunnison, and Colorado River.

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.).

Recommended New Studies Related to Fine Sediment Mass Balance

To monitor the effect of peak flow regimes on fine sediment mass balance in reaches important to endangered fish in the Upper Basin, we recommend two gages to evaluate sediment transport in the middle Green River: (1) near the existing Jensen, Utah, stream gage (USGS 09261000) [2]and (2) near the existing Ouray, Utah, stream gage (USGS 09272400). 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. Opportunities for cost sharing with other federal agencies should be explored.

Monitoring of suspended sediment transport and fine sediment mass balance is considered a lower priority in the lower Green River and lower reaches of the upper Colorado River. These lower priorities 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.

4 IMPLEMENTATION OF STUDIES

As described in Section 3, this Technical Supplement focuses on remaining high priority information needs and monitoring of related long-term systemwide trends. Five topics related to the role of peak flows in building and maintaining important fish habitats are addressed in this Technical Supplement: (1) peak flows needed to maintain the connection of floodplain wetlands to the main channel; (2) peak flows needed to maintain spawning habitats and other gravel and cobble-bed benthic habitats; (3) peak flows needed to build and maintain connected backwater habitats; (4) peak flows needed to prevent channel narrowing; and (5) peak flows needed to maintain the mass balance of fine sediment. Filling these remaining high priority information needs is considered necessary for establishing scientifically based peak flow recommendations.

The priorities identified in this Technical Supplement 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 Technical Supplement are relative to their importance to resolving peak flow uncertainties and not to overall priorities of the Recovery Program.

[2] An acoustic sediment gage at the Jensen site has been recently deployed by the USGS (D. Topping, pers. comm.).

The approach presented in this Technical Supplement emphasizes the need for monitoring changes in habitats and critical flow and sediment variables through time. Some of the suggested monitoring is continuous (e.g., suspended sediment transport) whereas others would be less frequent (e.g., measurement of channel narrowing; aerial surveys of backwaters; surveys of levee breaches and inflow channels of floodplain wetlands). In addition to recommended monitoring, a targeted study to estimate bed-load transport in the Gunnison River over a series of years is recommended.

We recognize the possibility that funding limitations will likely 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 Technical Supplement. In some cases there is overlap between the studies proposed here and in other recent study plans (e.g., the LTSP). 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 studies (e.g., aerial or satellite imagery to measure channel narrowing and survey backwater), 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 Technical Supplement 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 information gathered from studies identified in this Technical Supplement would contribute to ongoing evaluations of the Recovery Program flow recommendations. Formal evaluation of all aspects of the flow recommendations, including peak flow components, will follow the schedules identified in the Green River and Aspinall Study Plans.

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APPENDIX

ESTIMATED COSTS OF NEW ACTIVITIS IDENTIFIED IN THE PEAK FLOW TECHNICAL SUPPLEMENT

TABLE A1. Estimated Costs of New Projects Identified In the Peak Flow Technical Supplement

Topic/Project Activity	Reach and Priority	Start-up or Periodic Cost	O&M Cost	Comments
1. 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	
2. Spawning and Other Gravel and Cobble-Bed 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.
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	

Table A1 (Cont.)

Topic/Project Activity	Reach and Priority	Start-up or Periodic Cost	O&M Cost	Comments
3. Connected Backwater Habitats				
Survey number and surface area of backwater habitats using aerial or satellite imagery of study reaches.	Middle Green River (Split Mountain to Desolation Canyon), High	$15,000 to $50,000/ study reach	NA	Should be re-evaluated every 5-10 yrs. Use of satellite images or commercially available aerial imagery (e.g., free NAIP imagery) is the less expensive approach.
	Lower Green River (Gray Canyon to Colorado River), Medium priority	$15,000 to $50,000/study reach	NA	
4. Channel Narrowing				
Evaluate aerial or satellite 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 or commercially available aerial imagery (e.g., free NAIP imagery) 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	
5. Fine Sediment Mass Balance				
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			Some cost share available for sediment monitoring at Jensen site. All other sites represent full start-up and O&M costs. 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), High priority			
	Near Cameo gage, High priority	$35,000	$20,000	
	Near CO / UT Stateline gage, High priority	$35,000	$20,000	
	Near Potash, Medium priority	$35,000	$20,000	

Table A1 (Cont.)

Topic/Project Activity	Reach and Priority	Start-up or Periodic Cost	O&M Cost	Comments
Establish network of suspended sediment transport and fine sediment mass balance monitoring stations in critical reaches (Cont.)	Lower Gunnison River (Hartland Dam to Colorado River), High priority			
	Near Delta	$20,000	$20,000	
	Near Grand Junction gage	$20,000	$20,000	