Analysis of the Potential Implementation of a Rapid Response High Flow Experiment

October 15, 2012

Prepared By:

S. Clayton Palmer
Wayne E. Cook
Craig Ellsworth
Shane Capron
Jerry Wilhite

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A high flow experimental (HFE) protocol for Glen Canyon Dam is currently being implemented to improve our ability to build and maintain beaches in Marble and Grand Canyons. Two approaches have been developed: the store and release and rapid response HFE protocols. These protocols are intended to take advantage of sediment inputs from occasional Paria River floods. The store and release approach allows sand to accumulate in the mainstem from Paria River inputs, then during certain windows a flood may be triggered based on the sediment retained in the mainstem. However, because most of the sediment from the Paria River is composed of silt and clay rather than sand, a substantial portion of the annual sediment input from the Paria River would likely be transported out of the Grand Canyon before a flood is initiated under the store and release protocol.

A rapid response protocol was proposed as an alternative to better conserve this fine sediment. The rapid response approach utilizes a shorter duration and smaller magnitude flood that occurs simultaneously with a flood event from the Paria River. The rapid response protocol is based on concepts first described by Lucchitta and Leopold (1999) and Rubin *et al.* (2002). Under the rapid response protocol, a powerplant capacity HFE is implemented coincident with a Paria River sediment input by timing releases from Glen Canyon Dam. The advantage of the rapid response approach is that not only sand, but suspended silt, clay, and organics are also available to be deposited during a flood. Conservation of silt and clay has been identified as an important consideration because they can serve as an adhesive that binds sand deposits together, making beaches less prone to erosion. Additionally, organics may provide important nutrients for the aquatic foodbase downstream of Lees Ferry. A rapid response HFE will require real-time monitoring of the Paria River to accurately determine the sediment load, protocols for timely responses by dam operators to Paria River inputs, and public notices to ensure safety for recreational users and property owners.

The Paria River is the single largest contributor of sand, silt, and clay to the Colorado River below Glen Canyon Dam (Rubin et al. 2002). Large sediment input events from the Paria River are primarily driven by summer and fall monsoonal storms that peak in August. Notification of an impending flood from the Paria River for a rapid response HFE could be obtained using a combination of river gages, rain gages, and weather radar. Kimbrel (2012) reported that during the months of October and November, an indicator flood of at least 2,000 cfs or a flow rate increase of at least 1,500 cfs/hr at the Kanab gage, had a 95% probability of resulting in a flood event of at least 1,500 cfs at the Lees Ferry gage 7 to 9 hours later. The assumption is that this correlation would hold true for the more frequent and higher intensity August and September flood events as well. Upramp rates of 4,000 cfs/hr would allow powerplant capacity flows to reach Lees Ferry within the 7 to 9 hour window of notification of a Paria River flood. While the rapid response HFE is not an electrical emergency, past experience has shown that operations at Glen Canyon Dam could respond safely to match a Paria River flood event. The actions taken to meet the power needs of the 2000-2001 California energy crisis demonstrated no fundamental safety or operational issue with operating the dam in a fashion similar to what would be required to accommodate the rapid response HFE.

Prior to the first test of a rapid response HFE, a standard operating agreement would need to be developed including agreements between Western and Reclamation, an electrical utility tied to Western's electrical system would have to agree to take the power, and a notification protocol would have to be developed to notify persons below the dam who might be affected by the change in operations. This paper provides a description of the timing and magnitude of floods from the Paria River and how high flow releases from Glen Canyon Dam could be timed to occur with Paria River floods. This paper also describes how operations at Glen Canyon Dam have been modified in the past to accommodate exceptional circumstances such as the 2000-2001 California energy crisis and how operations could be modified in the future to accommodate a rapid response HFE protocol.

INTRODUCTION: THE RAPID RESPONSE HIGH FLOW EXPERIMENT

A high flow experimental (HFE) protocol for Glen Canyon Dam is currently being implemented to improve our ability to build and maintain beaches in Marble and Grand Canyons. In December 2011, the U.S. Bureau of Reclamation (Reclamation) released an Environmental Assessment[1] (EA) that described an experiment to test an HFE protocol spanning a 10-year period (Reclamation 2011). The objective is to improve sediment-related resource conditions below Glen Canyon Dam. The HFE protocol will test a number of hypotheses regarding how variations in HFE timing, magnitude, duration, and frequency affect sandbar building and sand conservation in Marble and Grand Canyons. Authority for modifying discharges for the environmental benefit of Grand Canyon was provided to the Secretary of Interior with presidential approval of the Grand Canyon Protection Act (GCPA) of 1992.

Background

Based on findings from three HFEs (see summary by Melis 2011), two types of HFEs were specified in the EA (Reclamation 2011). The primary experiment was the store and release protocol which is similar to previous high flow tests, while the rapid response protocol was also included as a test requiring further analysis before implementation. While the timing is different, both approaches seek to utilize sediment inputs from Paria River floods; both build on knowledge that sediment inputs are rapidly transported downstream unless they are transported to an elevation higher than the river's fluctuating zone; and both approaches require a peak release of about 40,000 cubic feet per second (cfs). The EA identified the specific science question relating to the rapid response protocol as:

> **Research Question #4:** Is sediment conservation more effective [than the store and release protocol] when an HFE is held in rapid response to sediment input from the Paria River?

---

[1] Full title: Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020

The following is a short description of the two HFE approaches found in the 2011 EA (Reclamation 2011). The purpose of this discussion is to provide an overview of similarities and differences between the two approaches. Then, we will discuss the potential benefits and operational challenges of implementing a rapid response HFE and provide an analysis of how this type of HFE may be implemented.

Sediment scientists initially assumed sediment input from tributaries to the Colorado River below Glen Canyon Dam accumulated on the river bed over multiple years (Reclamation 1995). It was hypothesized that these sediment deposits could then be mobilized by a high magnitude flood which would redistribute those sediments to the shoreline – thus creating sandbars and backwater habitats for native fish. However, this theory was dismissed by Rubin *et al.* (2002). Their research indicated that the mainstem Colorado River does not store sand and other fine sediments as described in the EIS (Reclamation 1995). They found that most of the sand and other fine sediment coming into the Colorado River below Glen Canyon Dam was exported from Marble Canyon in a matter of weeks to months, depending on particle size. Rubin *et al.* (2002) suggested that in order to successfully redistribute new sediment inputs from the Paria River, HFEs should occur immediately following a flood event in order to retain as much sediment as possible before it is transported downstream.

Store and Release HFE

Protocols for fall and spring store and release HFEs are described in the EA (Reclamation 2011). The fall sediment accounting period is from July 1 - Nov 30 and the fall HFE window is from Oct 1 - Nov 30. The spring sediment accounting period is from Dec 1 - Jun 30, and the spring HFE window is from Mar 1 - Apr 30. During each of these accounting periods, GCMRC would monitor the input of sand from the Paria River in the mainstem, and at the end of one of these two accounting periods, a sand budget would be created (e.g., input minus export) using a sand routing model. If enough sand is present, a sand model is used to test a series of high flow events (see Table 4 in Reclamation 2011). The flood that results in the largest magnitude and duration flood with a positive sand mass balance in Marble Canyon would be implemented during the appropriate HFE window.

A store and release approach allows some flexibility in scheduling an HFE which allows ample time to advise resource managers and the public of changes to operations at Glen Canyon Dam. This approach is most effective for sand-sized sediment particles because finer sediment particles including silts, clays, and organic matter are transported downstream before a store and release HFE could be implemented (Rubin *et al.* 2002). The amount of fine sediment available depends in part on the timing of the Paria River inputs and the subsequent HFE, which is predicted to be within a few months of a Paria River sediment input.

Rapid Response HFE

Lucchitta and Leopold (1999) first considered the notion of a rapid response HFE by proposing high dam releases be made to match floods from the Little Colorado River. Rubin *et al.* (2002) proposed a similar strategy, but proposed increasing releases from Glen Canyon Dam immediately following a Paria River flood. The rapid response protocol proposed by Western in 2010, proposes to conduct a rapid response HFE during a Paria River flood, taking immediate advantage of sediment inputs from the Paria River. Reclamation (2011) identified the rapid response HFE as a concept that should be tested as part of actions considered in that EA once several issues could be resolved.

The store and release protocol utilizes suspended sand concentration measured in a laboratory, sand budget models, and sand routing models to determine magnitude and duration of HFEs to occur at some time in the future. The proposed rapid response protocol, on the other hand, would require real-time measurements of flood events in the Paria River to trigger HFEs. Currently, no means exist to obtain real-time measurements of sediment input from the Paria River, and existing models for sediment input and transport are not calibrated to estimate retention or transport of particle sizes finer than sand. Discharge could be used as a surrogate, but the relationship between discharge and sediment input is less than ideal (Kimbrel 2012). Minimum sediment input required to initiate an HFE would need to be established, and equipment capable of providing real-time information on sediment input would need to be installed or models capable of estimating sediment input would need to be developed to refine our ability to determine if this minimum threshold was achieved. Once it is determined conditions to trigger an HFE are present, information would need to be transmitted to dam operators in sufficient time so they can release water from the dam to coincide with the flood input from the Paria River. The decision to implement a rapid response HFE must occur within a matter of hours. The success of the rapid response approach requires coupling of Paria River floods and dam releases to deposit sediment at an elevation above the high water mark for normal operations.

There are several potential positive effects on various resources downstream from Glen Canyon Dam:

- The potential to build and maintain ecologically important sandbar complexes with greater efficiency than the storage and release approach for HFEs.
- An advantage in delivering high suspended sediment concentrations downstream, which has been shown to exert primary control on the building of sandbar complexes in previous HFEs.
- Matching rapid response HFE releases to a Paria River flood may require less water to be released from the dam during the experiment.
- More frequent high-flow events with more variability with respect to their magnitude, frequency, and timing, which can potentially deliver a greater amount of sediments to sandbar complexes (Kimbrel 2012).
- A greater storage and deposition of fine, cohesive sediments (silts and clays) along with organic material that can help stabilize sandbars as well as enhance productivity in backwater habitats.

There are, however, several issues that need to be addressed prior to testing of this approach, including:

- It relies on the flow of the Paria River as the trigger for the HFE. The rapid response decision framework requires short-term decisions that must be based on the progression of floods in the Paria River. These floods are highly variable and of short duration, often 24 hours or less.

- The models used to develop and implement an HFE under the store and release protocol are not capable of evaluating the retention of sediment and organic matter finer than sand. These models could possibly be developed with further refinement of the existing sand budget model.
- Prior to the initiation of a rapid response HFE, an appropriate warning system would need to be developed. An effective warning system will require coordination with dam operators and notices to anglers, boaters, rafters, and recreationists to ensure public safety.
- Average monthly sand load from the Paria River is greatest in August and September. Therefore, a rapid response HFE would most often be triggered in these months, which are outside the HFE release windows outlined in the EA (March-April and October-November).
- It is unclear how a large input from the Paria River during a time of low sediment storage in the mainstem Colorado River would affect the results of a rapid response HFE. Further understanding of the kinematic wave generated by a rapid response HFE is needed.

Reclamation (2011) intends to test a rapid response HFE as soon as practicable within the same release windows (March-April and October-November) as identified in the 2011 EA (Reclamation 2011). Implementation of a rapid response HFE will also require the development of a science plan and modification of existing communication systems and dam operations protocols. Reclamation (2011) also indicated that additional NEPA compliance may be needed to evaluate the impacts of a rapid response HFE outside the October-November and March-April release windows.

PARIA RIVER FLOODS

Before a rapid response HFE protocol can be fully developed, we must first investigate the characteristics of Paria River floods and evaluate the effectiveness of current monitoring systems. Until more reliable sediment monitoring is available, this rapid response approach relies on the flow of the Paria River as the trigger for an HFE. Implementation of this rapid response approach requires short-term decisions based on real-time information of floods in the Paria River. These floods are typically highly variable and of short duration. Kimbrel (2012) evaluated Paria River floods, and those findings are incorporated here to inform discussions about Glen Canyon Dam operations and the potential to conduct a rapid response HFE.

The Paria River has been the largest contributor of sand, silt, and clay to the Colorado River below Glen Canyon Dam since sediment inputs from the Little Colorado River began declining in the mid-1980s (Rubin *et al.* 2002). The amount of sediment coming into the Colorado River when the Paria River is at flood stage is often substantial but highly variable (Figures 1 and 2). Concentrations of fine sediment (clay, silt, and sand smaller than 0.25 mm), at the confluence with the Colorado River, immediately following a flood event, frequently reach levels comparable to those measured in the Colorado River prior to the closing of Glen Canyon Dam (Rubin *et al.* 2002). However, these sediment inputs are relatively rare and account for only 6% of the pre-dam average annual sediment load in the Colorado River (Rubin *et al.* 2002).

Effective management of these sporadic sediment inputs has been identified as being critical for maintaining the remaining beaches and other sediment-related habitat in Marble Canyon.

Figure 1. David Rankin, a resource specialist at the Glen Canyon National Recreation Area, filming a flash flood and debris flow coming down the Paria River on August 19th, 2012. This is an example of the concentration of organic material the Paria River can contribute to the mainstem Colorado River during a flood event. Photo by Heather Rankin, used with permission.

Frequency and Magnitude of Paria River Floods

The Paria River is ephemeral with occasional short-duration flood events. These short-duration floods may occur at anytime of the year, but occur most frequently during the monsoon season from July to September (Figure 3). Heavy winter rainstorms or rain-on-snow events can produce short-duration high flow events during the late winter and early spring as well. The maximum recorded peak flow of the Paria River at Lees Ferry was estimated at 16,100 cfs in 1926. Annual peak flows at Lees Ferry from 2000 to 2010 averaged 2,486 cfs, and floods greater than 2,500 cfs occurred at least once in 4 of those 11 years.

Paria River sediment inputs are primarily driven by summer and fall floods. Summer and fall monsoonal storms are more likely to erode hillslopes in the upper basin than winter snowmelt or rain-on-snow events and therefore carry more fine sediments than winter storms (Rubin *et al.* 2002). Most summer and fall floods are caused by intense thunderstorm activity in the uppermost 14% of the basin (Topping 1997). Floods in the Paria River are generally high in intensity but short in duration. Bankfull discharge in the Paria River is 3,178 cfs and occurs on average every 2.2 years (Topping 1997). Floods greater than bankfull discharge are rare and are generally short with a mean duration of 3.66 hours (Topping 1997). Floods along the length of Paria River are typically conveyed with little modification or attenuation. Topping (1997) reported that for the period of record (1923-present), flood peaks typically decreased by less than 33% from Cannonville to Lees Ferry and noted that some floods increased by as much as 300%.

Figure 2. Turbid water carrying fine sediment (silts and clays) from the Paria River mixing with clear water from the mainstem Colorado River at Lees Ferry. Note the recently deposited sand visible in the middle of the river channel (March 2012).

Examples of Paria River Floods

Multiple floods per year can occur in the Paria River as illustrated in the 2010 hydrograph measured at Lees Ferry (Figure 4). In 2010, there were four flood events on the Paria River measuring over 1,000 cfs with peak flows in two of those events exceeding 2,500 cfs. The first three flood events were the result of summer and early fall thunderstorms with the fourth occurring in late December as a result of an extended rain or possibly a rain-on-snow event.

The first Paria River flood occurred in the first part of August and was the result of wide-spread thunderstorm activity in the drainage. A flood on August 4th peaked at 2,056 cfs and was followed by a second event on August 8th that peaked at 5,618 cfs. The August 4th flow was of short duration with the peak flow dropping to 145 cfs the following day. The August 8th event was of longer duration with flows of 1,694 cfs being recorded on the 9th before dropping below 100 cfs on the 10th. Neither weather station in Cedar City, UT nor in Page, AZ recorded precipitation on August 4th. However, on August 8th 0.90” of rain was recorded in Cedar City and

0.15” of rain was recorded in Page. A third flood occurred in the first part of October which exceeded 2,300 cfs for three days, with a peak of 3,635 cfs on October 6th. From October 5th to 7th there was widespread thunderstorm activity in the area. During this time, the weather station at Cedar City recorded a total of 1.45” of rain and the weather station in Page recorded a total of 1.67” of rain. The fourth flood occurred in late December following what was an extended rain or possibly a rain-on-snow event. As with the October flood, peak flows in the Paria River at Lees Ferry were elevated for three days; peaking at 1,143 cfs on December 21st. There were four days of consistent rain in the drainage from December 20th to the 23rd. During these four days, the weather station at Cedar City recorded a total of 1.70” of rain while the weather station in Page recorded 0.19” of rain.

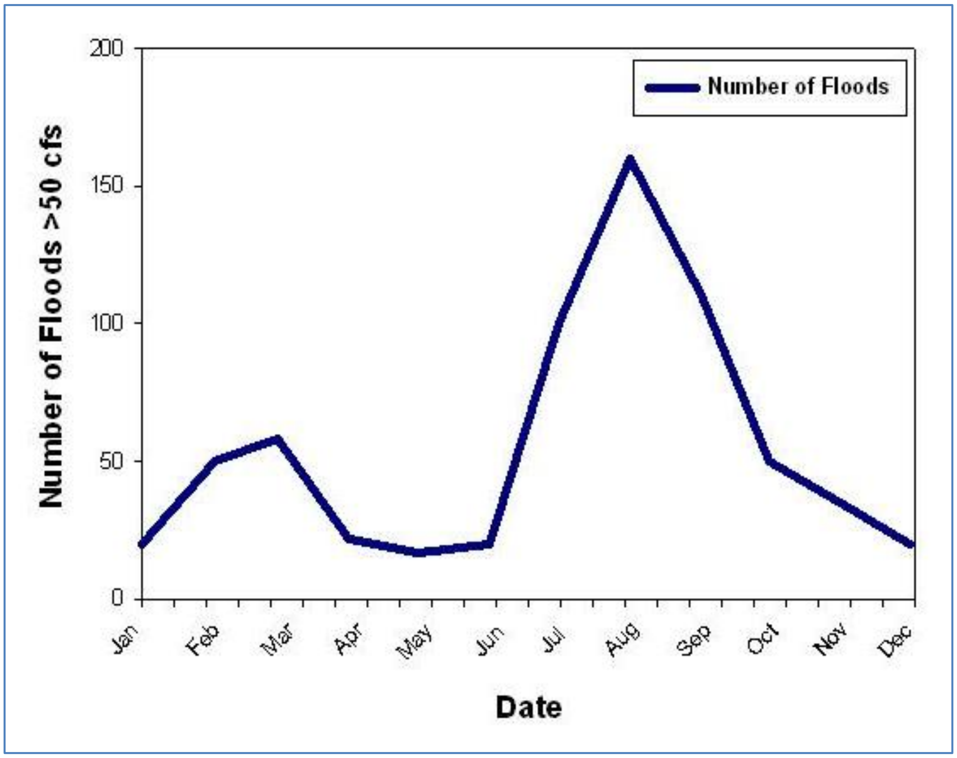

Figure 3. Total number of floods on record in the Paria Canyon by month (http://www.blm.gov/az/st/en/arolrsmain/paria/climate.html).

Understanding the storm patterns in the Paria River drainage may improve our understanding and ability to predict the annual discharge patterns. For example, in 2010, fall and winter floods were of longer duration than summer floods. However, summer floods tended to be more intense. Storms during the fall, winter, and spring typically have a wider geographic distribution and duration, and thereby probably produce more predictable floods than isolated summertime thunderstorms.

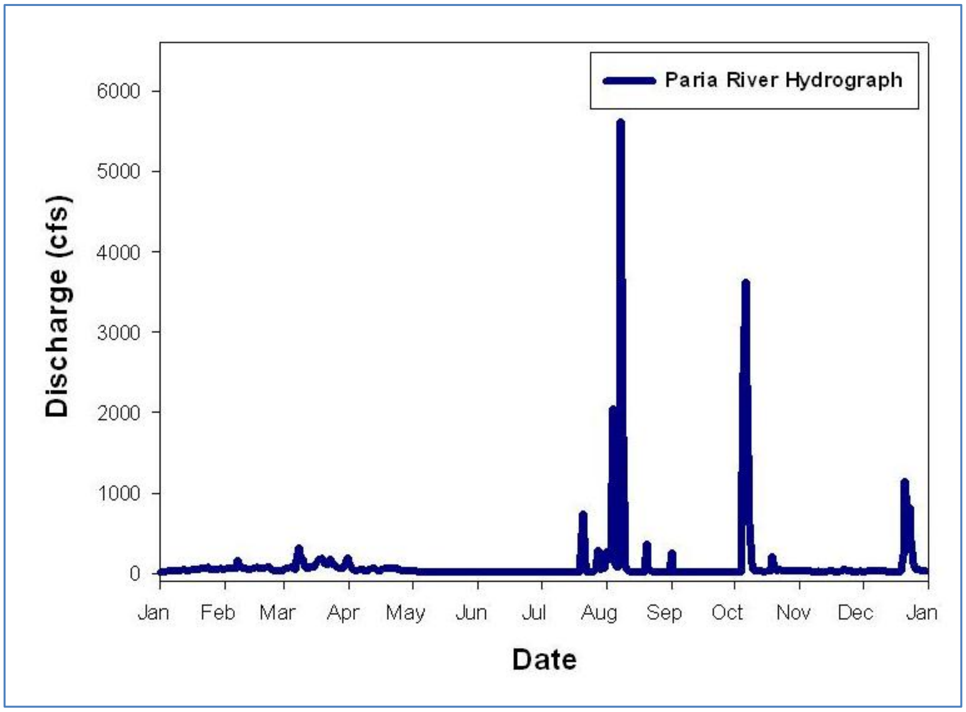

Figure 4. Hydrograph for the Paria River at the Lees Ferry gage (USGS gage #09382000) in 2010 showing the daily maximum discharge.

Advance Warning of Paria River Floods

A rapid response HFE would require Glen Canyon Dam operators to time increases in discharge so that flood waters reach the Paria/Colorado River confluence during a Paria River sediment input. To overcome the feasibility issues identified by Rubin *et al.* (2002), dam operators would need sufficient notice of an impending flood to release water in time to have that water arrive at the confluence with the Paria River during a flood event. Such a notification system could be developed using a combination of river gages, and possibly rain gages and weather radar.

USGS has operated three river gages on the Paria River between its headwaters near Cannonville and its confluence with the Colorado River (Figure 5). Two of these gages, the Kanab gage and the Lees Ferry gage, are currently in operation (Figure 6). The Kanab gage (USGS gage # 09381800) is operated by the Utah Water Science Center in Cedar City, UT. The Kanab gage is located at 37°06'27" N, -111°54'19" W at the Highway 89 crossing which is approximately 38.8 river miles upstream of the confluence with the Colorado River. The catchment above the Kanab gage is approximately 647 mi^2. The period of record for the Kanab gage is from 2002 to the present. The Lees Ferry gage (USGS gage # 09382000) is operated by the Arizona Water Science Center in Flagstaff, AZ. The Lees Ferry gage is located at 36°52'20" N, -111°35'38" W and is approximately 1.0 river mile upstream of the confluence. The catchment above the Lees Ferry gage is approximately 1,410 mi^2. The period of record for the Lees Ferry gage is from 1923 to the present. Discharge data for both the Kanab gage and the Lees Ferry gage are updated at 15 minute intervals and are available on the USGS website. The equipment for the third Paria River gage near Cannonville (USGS gage # 09381500) is still on site, but this gage has not been in operation since 2006. The Cannonville gage has been operated intermittently by the USGS since it was established in 1950, and is the furthest upstream gage on the Paria River (located 73.3 river miles from the Colorado River at 37.480556° N, 112.260000° W). The gage has a period of record from 1950 to 1955 and 2002 to 2006.

Kimbrel (2012) investigated the utility of using discharge data from two USGS gages to predict a Paria River flood reaching the Colorado River at Lees Ferry. Hydraulic data from the Kanab (upstream) and Lees Ferry (downstream) gages on the Paria River, for the period of record where both gages were in concurrent operation, were statistically analyzed to determine if flow parameters at the upstream gage could be used to predict flood events of specified magnitudes with 95% probability at the downstream gage. Kimbrel (2012) noted that flood events at the Lees Ferry gage could be determined with a certain level of probability based on flows passing the Kanab gage. Results indicated that a flood in October and November of about 2,000 cfs or a ramp rate of about 1,500 cfs per hour at the Kanab gage resulted in 95% probability that a flood event of at least 1,500 cfs would occur 7 to 9 hours later at the Lees Ferry gage. An analysis of all floods occurring throughout the entire year only yielded a 45% chance of predicting a flow of this magnitude at the Kanab gage reaching the Lees Ferry gage using these parameters. Floods in the Paria River, however, typically occur from July to September (see Figure 3), which is different than the October to November timeframe analyzed by Kimbrel (2012). One could expect that a similar analysis of July to September floods would yield comparable results to October to November floods with the former occurring more frequently and possibly with greater intensity.

One important consideration Kimbrel (2012) noted in using floods from the Paria River to implement a rapid response HFE is sediment concentration, storage, and river bed evolution in the Paria River are not perfectly correlated with discharge. While sediment concentration can be affected by discharge, recent flow history also significantly influences sediment concentration. It currently is not possible to use instantaneous flow observations in the Paria River to determine a sediment-based trigger for a rapid response HFE since there is no means to quickly estimate the amount of sediment a particular Paria River flood event is being transported into the mainstem Colorado River during a flood. Analyses for sediment concentration are currently done post-flood in a laboratory by GCMRC scientists.

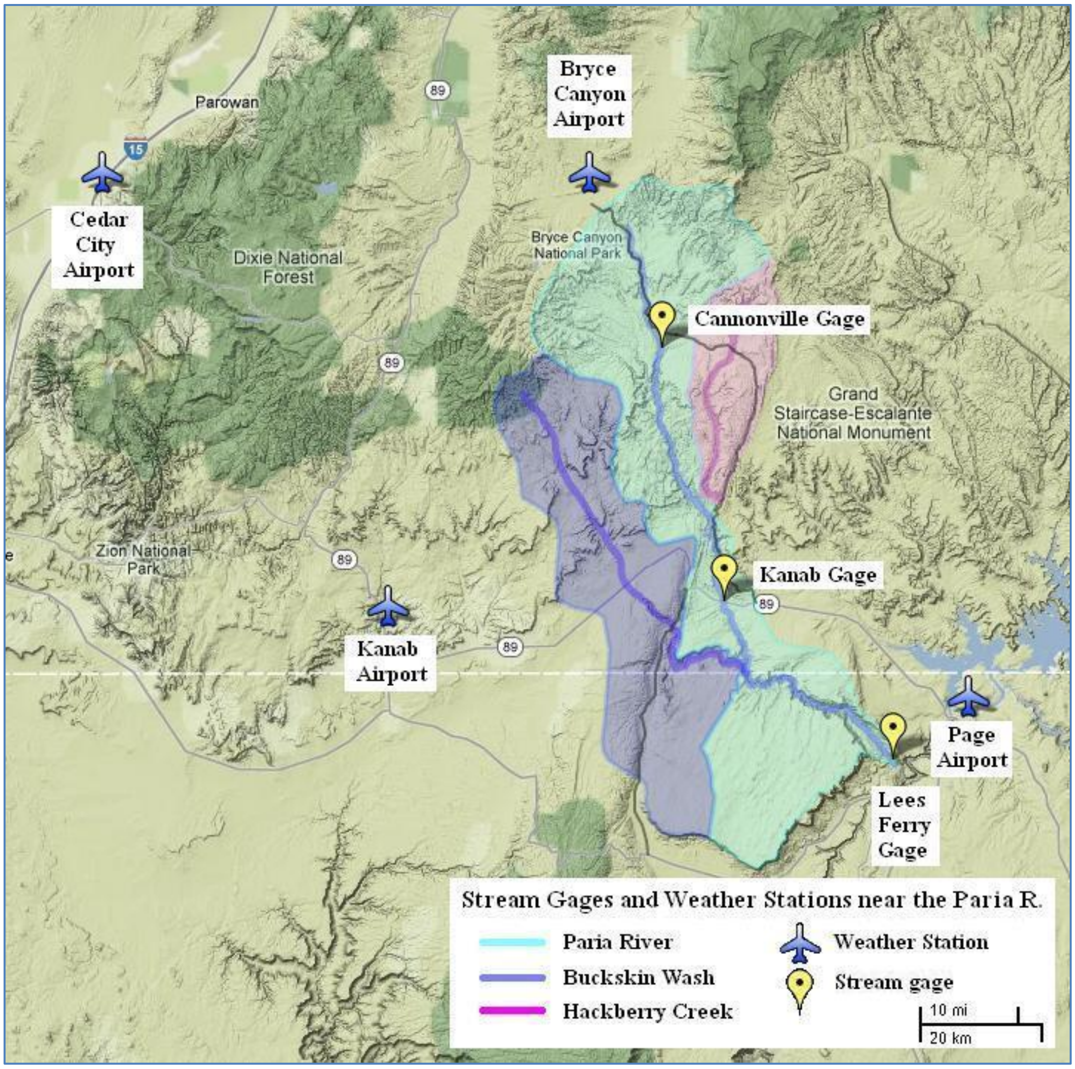

Figure 5. Locations of the U.S. Geological Survey (USGS) stream gages and the National Weather Service (NWS) weather stations near the Paria River.

Figure 6. The Paria River gage near Kanab, UT at the U.S. 89 bridge crossing (left) and the Paria River gage at Lees Ferry, AZ upstream from the Colorado River (right).

Predicting Paria River Floods

Next, we consider how these stream gages could be used with National Weather Services (NWS) weather stations to predict a Paria River flood of sufficient magnitude to consider a rapid response HFE. The NWS maintains a network of monitoring equipment that is designed to give advanced warning of storms that may lead to flooding in a watershed such as the Paria River. These networks provide information that is used for everything from forecasting an increase in monsoonal activity across the desert southwest to instantaneous rainfall data falling in a localized area. Some of the longer range forecasts, such as tracking weather patterns that drive the monsoon, can be extended several weeks in advance while instantaneous data can be used to estimate magnitude, timing, and duration of impending flood events down to the sub-watershed level.

The NWS operates local weather stations at Bryce Canyon Airport near Cannonville, Kanab Municipal Airport, and Page Municipal Airport (Figure 5). These weather stations record hourly weather data that include precipitation, temperature, barometric pressure, and wind direction and speed. The NWS also maintains a long-term weather data set for Cedar City, UT and Page, AZ. Cedar City also provides regional weather radar, severe thunderstorm and flashflood warnings, storm and 1-hour precipitation totals along with weather data on a 5-minute interval. These data are all available on NWS websites and could be used to evaluate the potential for a Paria River flood event (see Appendix A).

The first warning issued by the NWS is a severe storm warning, which would apply to both summer and winter storm events. The NWS then monitors storm total and 1-hour precipitation totals, both of which are available online for the weather stations identified in Figure 5. If models indicate that precipitation levels are sufficient to produce a flood, the NWS issues a flood or a flash flood warning depending on the severity of the precipitation event. This would alert resource managers of a potential Paria River flood in the immediate future. If the NWS issues a flood or a flash flood warning, resource managers could then start monitoring weather radar, storm total, and 1-hour precipitation totals on the NWS website and the streamflow gage data on the USGS website for indications of a flood in the Paria River.

A review of several recent storms shows that a flood coming from a storm centered high in the drainage (i.e. above the Kanab gage) typically takes 6-10 hours to travel from the Kanab gage to the Lees Ferry gage. Figure 7a illustrates a summer flood occurring on August 4, 2010 on the Paria River showing a travel time of approximately 6:45 hours between the Kanab gage (dark blue solid line) and the Lees Ferry gage (light blue dotted line). This is within the range of the 7 to 9 hour time lag from when a flood is registered at the Kanab gage to when it reaches the Lees Ferry gage reported by Kimbrel (2012).

The rate at which these floods progress downstream is likely variable depending on the amount of water being delivered downstream with larger floods arriving downstream in a shorter amount of time. Where the flood originates may also influence one’s ability to predict its travel time between gages. A flood originating below the Kanab gage may appear to have traveled unusually fast downstream to the Lees Ferry gage. Figure 7b illustrates a flood with an apparent travel time of approximately 4:45 hours between the Kanab and Lees Ferry gages. This could be a situation where a portion of the flood originated below the Kanab gage and had less distance to travel before reaching the Lees Ferry gage. Although the Kanab gage appears to be a good indicator of floods originating in the upper reaches of the basin, some floods likely originate from below the Kanab gage and are probably only partially observable with the current gaging system. This could lead to a flood reaching the Lees Ferry gage before it was expected based on observations at the Kanab gage alone.

In addition to identifying timing differences in floods based on where summer and fall thunderstorms are centered, there may also be timing differences between floods generated by thunderstorm events vs. floods generated by rain-on-snow events. Thunderstorms often create flash floods that are high in intensity yet short in duration. Rain-on-snow events can also create floods, but these floods are not generated as quickly and will typically last longer than floods generated by thunderstorms. Figure 8 is an illustration of a winter flood event recorded in 2005 when the Cannonville gage was in operation. This flood took approximately 6:15 hours to travel from the Cannonville gage (solid blue line) to the Kanab gage (dotted blue line) and approximately 14:15 hours to go from the Kanab gage to the Lees Ferry gage (dashed blue line). Also, note that the leading edge of all three hydrographs are not as sharp as those seen in a summertime flash flood and that there is a decrease in peak flows at the Lees Ferry gage (the gage furthest from the rain-on-snow event) and an attenuation in flow between upstream and downstream sites.

Increasing the number and distribution of stream gages in the Paria River drainage could increase the reliability and response time of using upstream flows to predict the timing and magnitude of a flood at Lees Ferry. For example, Figure 8 shows a flood coming down the Paria River when the Cannonville gage was in operation. The flood travel time between the Cannonville gage and the Kanab gage appears to be approximately 6:15 hours. Incorporating data from the Cannonville gage with data from the Kanab gage could have increased the early warning of this flood to approximately 14:15 hours before it reached Lees Ferry. However, using gages further from Lees Ferry may also increase the probability of floods that produce a false positive trigger for a rapid response HFE. The flood event portrayed in Figure 9, for example, shows a flood event at the Cannonville gage where most of the input apparently occurred high in the drainage. By the time the flood reached both the Kanab gage and the Lees Ferry gage, flows had attenuated enough to produce what ended up being only a modest flood at Lees Ferry. This is in contrast to the flood event portrayed in Figure 8 where the flood peak at Lees Ferry reached about 50% of the flood peak recorded at the Cannonville and Kanab gages. Figure 10 shows a similar example of what appears to be a false positive flood at the Kanab gage also resulting in only a modest flood at Lees Ferry. The installation of additional gages in the Paria River basin could help reduce the possibility of a false positive flood triggering an HFE or increase the detection probability of floods that occur below the Kanab gage. For example, the installation of a gage on Buckskin Wash, possibly at House Rock Valley road, may help identify floods coming from the Buckskin Wash drainage and into Paria River below the Kanab gage. These examples demonstrate the importance of developing adequate triggering protocols and possibly the need for incorporating additional data sensing capability to the rapid response HFE protocol than solely relying on a reading at Kanab gage to predict a flood event at Lees Ferry.

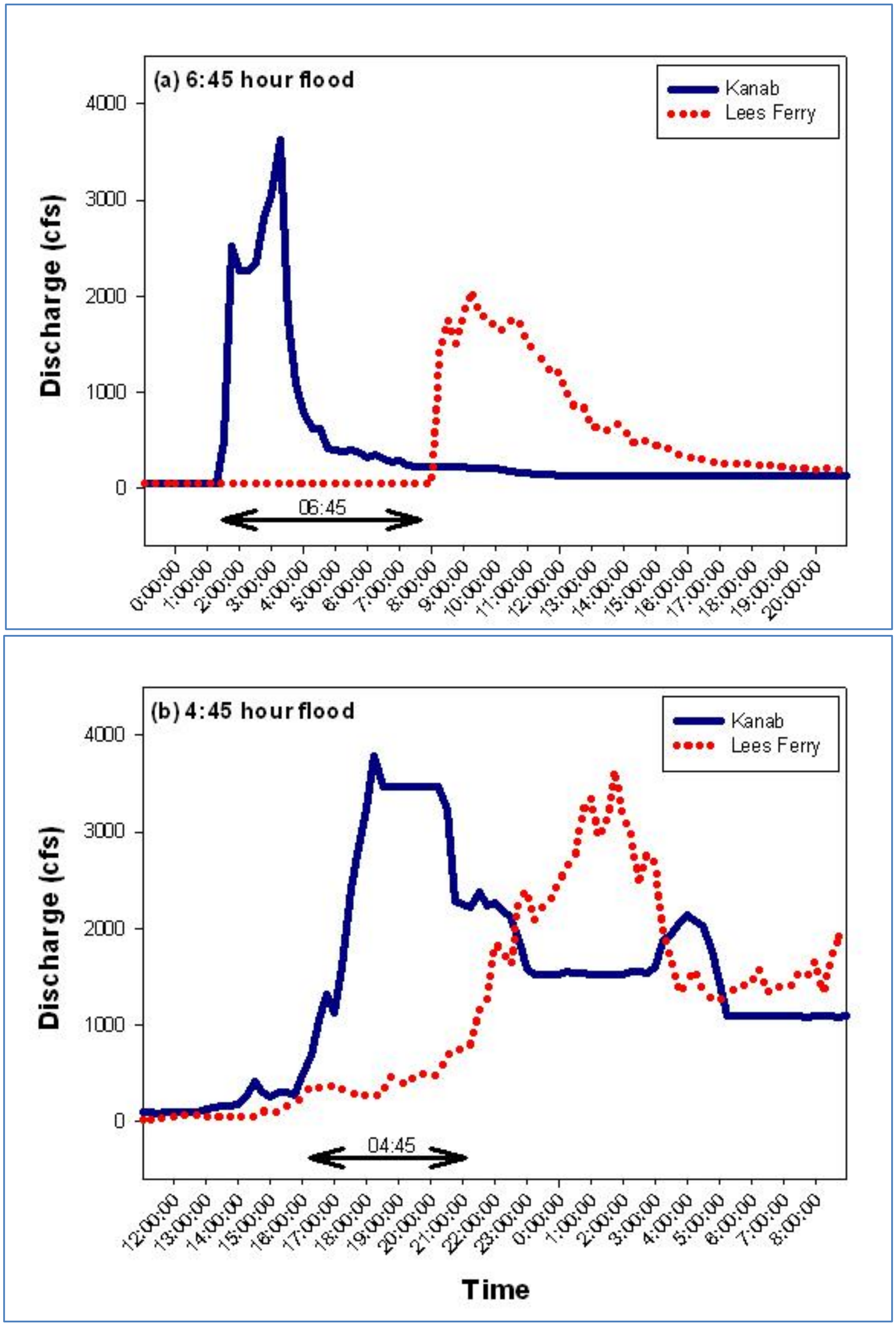

Figure 7. A summer flood occurring on August 4, 2010 at the Kanab gage on the Paria River (USGS gage # 09381800) with a travel time of approximately 6:45 hours to the Lees Ferry gage (USGS gage # 09382000) at the Colorado River (top panel, a), and a fall flood on October 5-6, 2010 with a travel time of approximately 4:45 hours to the Lees Ferry gage (bottom panel, b).

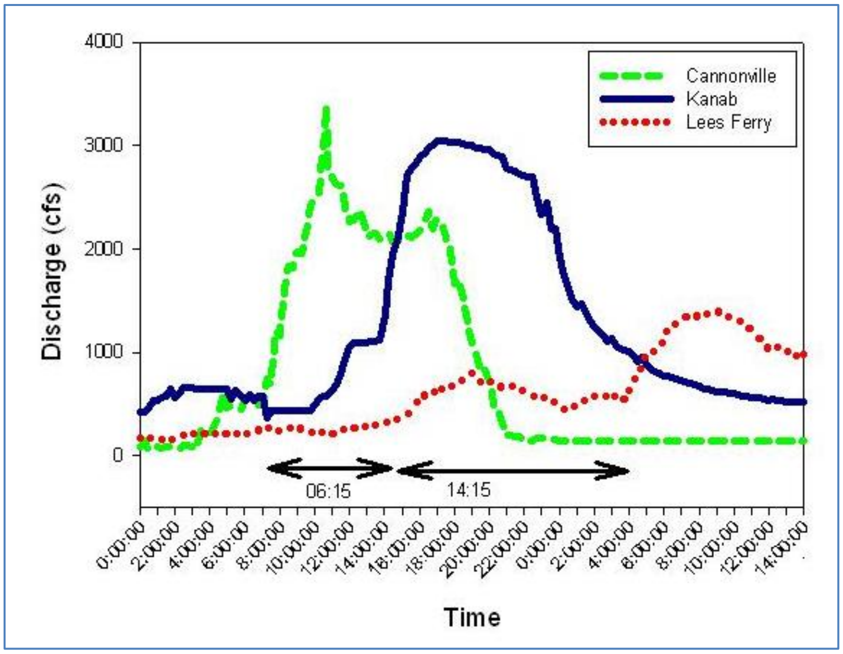

Figure 8. A winter flood occurring on the Paria River on January 10-12, 2005 recorded in sequence from the Cannonville gage (USGS gage # 09381500) to the Lees Ferry gage (USGS gage # 09382000). Figure shows flood travel time between the Cannonville gage and the Kanab gage (6:15 hours) and between the Kanab gage (USGS gage # 09381800) and the Lees Ferry gage (14:15 hours).

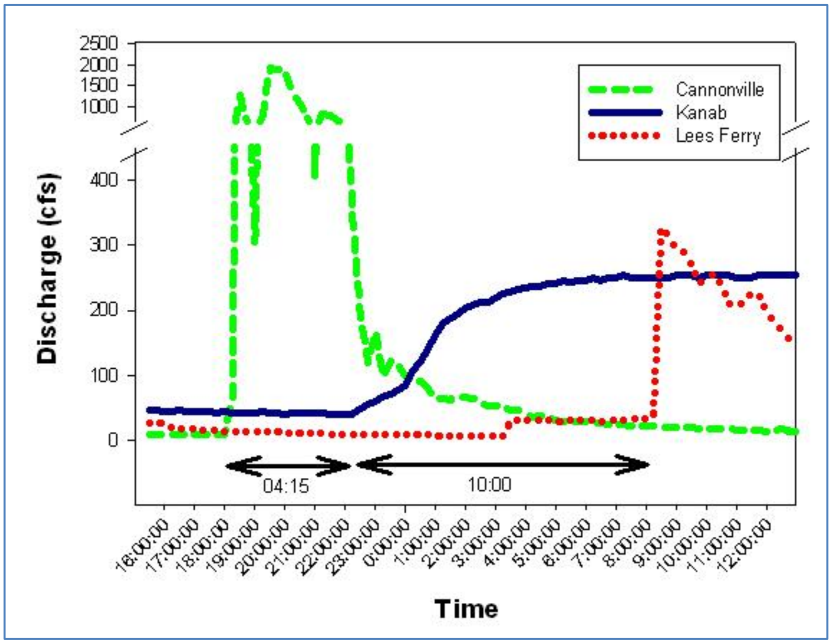

Figure 9. A flood occurring on the Paria River on August 20-21, 2004 being recorded in sequence from the Cannonville gage (USGS gage # 09381500) to the Lees Ferry gage (USGS gage # 09382000). Figure shows both flood travel time between the Cannonville gage and the Kanab gage (4:15 hours) and between the Kanab gage (USGS gage # 09381800) and the Lees Ferry gage (10:00 hours) and is an example of a large flood occurring high in the drainage that attenuates to only a modest flood lower in the drainage.

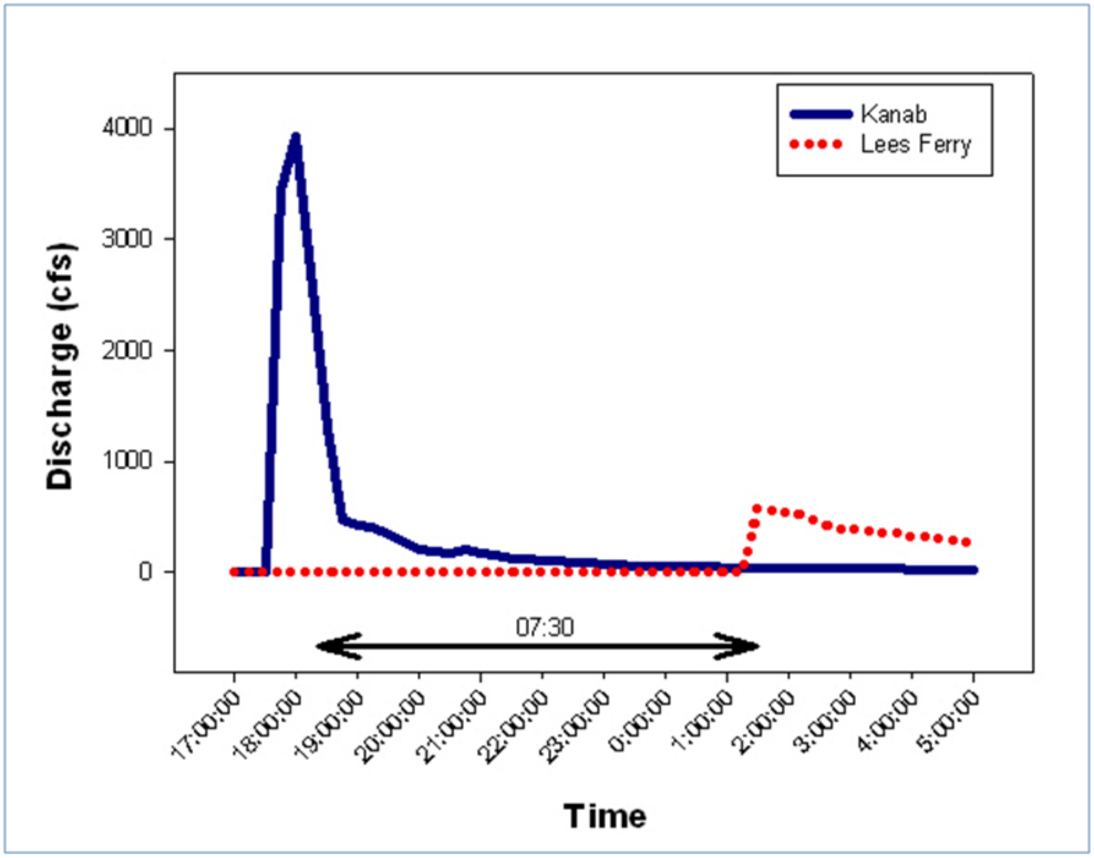

Figure 10. A high intensity, short-duration flood occurring on August 16-17, 2008 at the Kanab gage on the Paria River (USGS gage # 09381800) that had attenuated to only a modest flood by the time it reached the Lees Ferry gage (USGS gage # 09382000) at the Colorado River.

RAPID RESPONSE OPERATIONS OF GLEN CANYON DAM

Previous sections of this document addressed the practicability of predicting flood events and presumably, large sediment inputs from the Paria River. The next step is to assess the feasibility of manipulating Glen Canyon Dam operations to implement a rapid response HFE coincident with Paria River floods. In particular, we need to know how quickly water releases from Glen Canyon Dam can be increased from normal operations to flood releases. While a rapid response HFE is not an electrical emergency, the information provided below shows that operational changes can be quickly and safely implemented at Glen Canyon Dam to respond to a Paria River flood event.

Normal Operations of Glen Canyon Dam

Annual release targets from Glen Canyon Dam are determined by storage conditions at Lake Powell, expected runoff, and criteria regarding water deliveries to the Lower Basin. Monthly release targets are developed by dividing the annual release volume into monthly targets while respecting peak-power months. These targets are adjusted as the forecast for Lake Powell inflows are updated.

Schedules for Glen Canyon Dam releases are prepared daily by Western's Energy Management and Marketing Office (EMMO) in Montrose, CO and are prepared one day in advance of their operation. Scheduled Glen Canyon Dam releases are made in concert with Reclamation's monthly release volumes determined by forecasted inflow and reservoir storage conditions. Daily and hourly release targets are restrained by operating criteria (Table 1), as specified by the 1996 Record of Decision (ROD; Department of Interior 1996) for the 1995 EIS (Reclamation 1995).

Table 1. Glen Canyon Dam Operating Criteria.

OPERATION	RELEASE
Minimum allowable release:	Daytime (7am-7pm): 8,000 cfs Nighttime (7pm-7am): 5,000 cfs
Allowable daily flow fluctuation (cfs/24h):	5,000 cfs for monthly releases <600,000 af 6,000 cfs for monthly releases between 600,000 af and 800,000 af 8,000 for monthly releases >800,000 af
Ramp rates:	Upramp: 4,000 cfs/hr Downramp: 1,500 cfs/hr
Maximum allowable release:	25,000 cfs

A release schedule for Glen Canyon Dam (and the other Salt Lake City Integrated Projects; SLC/IP) is first prepared by Western's CRSP MC Management and Technical Services division within the constraints of these criteria and using a target water volume provided by Reclamation. Western divides the monthly target into daily increments. Western, using the GT Max model, develops an hourly schedule for the typical weekday as well as independent Saturday and Sunday schedules for the entire month.

This schedule is provided to the EMMO division for the development of an electronic pre-schedule. Using the GT Max data, plus additional information, the EMMO develops the monthly final pre-schedule and enters it into the Phoenix Supervisory Control and Data Acquisition

(SCADA) system. The SCADA system is an electronic Industrial Control System (ICS); a computer software program that monitors and controls electrical processes. Western transfers electrical power information for Glen Canyon Dam from its SCADA system electronically to Reclamation's SCADA system which tracks and controls the operation of Glen Canyon Dam. The two systems are in constant communication and monitor power system performance on a second to second basis. Under normal operations, releases from Glen Canyon Dam are adjusted every four seconds throughout the course of the day according to the power system regulation needs of the grid and other factors. Instantaneous release fluctuations from Glen Canyon Dam have been constrained to ±40 megawatts (MW) and can occur without notice. Depending on the elevation of Lake Powell, this usually equates to changes of approximately ±1,000 cfs.

Unscheduled and Emergency Operations of Glen Canyon Dam

Operations at Glen Canyon Dam can be called on at a moment's notice to respond to electrical outages and other power-related emergencies. Glen Canyon Dam is typically called on several times a month to respond to emergency electrical situations to help maintain the integrity of the Western Interconnect power grid. Western and Reclamation are required to operate Glen Canyon Dam to meet Western Electricity Coordinating Council (WECC) and North American Electric Reliability Corporation (NERC) operating criteria by maintaining electrical reserves that can be called on in case of an outage or emergency. Electrical reserves are generating capacity that sit idle until a situation arises where they are needed. Electrical reserves can be activated instantaneously and when these reserves are called on, releases from Glen Canyon Dam increase in order to generate this additional power. Glen Canyon Dam typically carries 120 MW of reserves which equates to about 3,000 cfs of releases in order to activate.

On occasion, Glen Canyon Dam has also been called on to generate emergency power in excess of its reserve allocation to meet WECC and NERC obligations. Losing a major transmission line or generating unit on the interconnecting system may cause a system emergency by changing the frequency of the power system due to a mismatch between generators and the load resulting in high or low voltage readings in the transmission system and lead to customer outages. These disturbances can last up to a few hours and can result in release changes of up to 5,000 cfs if Glen Canyon Dam is called on to help regulate the grid.

Western belongs to two reserve-sharing groups, the Rocky Mountain Reserve Group (RMRG) and the Southwest Reserve Sharing Group (SRSG). If a reserve group member were to have a power generation facility go down, the other reserve group members would each increase their generation by a pre-determined amount to replace the missing generation. In the case of using generation at Glen Canyon Dam, the CRSP MC would increase generation at the powerplant by their proportional share of the group response. The power supplier that lost the generation has up to 1 hour and 59 minutes (RMRG) or 1 hour (SRSG) to replace the lost generation. Glen Canyon Dam could be called on to respond to emergencies in both Reserve Sharing Groups at the same time.

When an emergency occurs within SRSG, information concerning the emergency is processed by Western's Phoenix office. When an emergency occurs within RMRG, information concerning the emergency is processed by Western's Phoenix, AZ and Montrose, CO offices. When an emergency notification is received, computer software evaluates the emergency and the

Automatic Response System (ARS) terminal allocates the necessary responses to the individual members of the RMRG and/or SRSG units. Western's Phoenix office contacts Western's Montrose office to confirm which hydropower facility will respond to the emergency. Emergency changes in generation at Glen Canyon Dam is initiated by Western's Phoenix office in conjunction with Reclamation and documentation for each emergency is provided by Western to Reclamation's Control Center at Page, AZ. The 1997 Operating Agreement between Reclamation and Western concerning Glen Canyon Dam Operating Criteria further describes operational responses during emergencies. These revised Operating Criteria were signed by the Secretary of the Interior on February 24, 1997 in compliance with the Grand Canyon Protection Act of 1992 (Section 1804 of Public Law 102-575).

Response to the California Energy Crisis of 2000 – 2001

The operational response at Glen Canyon Dam to the California energy crisis of 2000-2001 demonstrated that operations at the dam can be adjusted to meet a specified need associated with the facility. The response also demonstrated that these adjustments can occur rapidly with actions being taken within minutes of the first notification that an operational change is needed. The actions taken to meet the power needs of the California Independent System Operators (ISOs) also showed there is no fundamental safety or operational issue with operating the dam in a manner outlined above for a rapid response HFE, and that under certain circumstances, discharge patterns outside of the 1996 ROD guidelines can be implemented to meet a warranted need associated with the facility.

Generally, power plant operators and control area dispatchers have little or no warning that an emergency is about to happen. However, in the example outlined below, operators and dispatchers usually had an hour or more of notice that a problem was occurring and had more time to take preventative actions. This example demonstrates that operational changes at Glen Canyon Dam, similar to what is required to accommodate a rapid response HFE, have already been successfully implemented in the past.

In the fall of 2000, the California ISOs determined that the electrical energy available in the Southern California Area was insufficient to meet the peak needs of its customers. The California ISOs identified that criteria established in response to a Presidential directive were met for a Stage III power emergency, including evidence that no additional power supplies were available. This directive mandated that federal power generation facilities, like Glen Canyon Dam, take all possible measures to maximize power importation into California under those circumstances. Western coordinated with the California ISOs to provide emergency peaking assistance on seven occasions between September 2000 and May 2001 to maintain stability in the power system servicing Southern California.

To obtain emergency power assistance, the ISOs were directed to first contact Western’s CRSP office in Montrose, CO to request assistance in meeting a defined short-term energy supply need. Western required that each emergency power delivery have an individual contract with a declaration that no other power was available to meet those needs and that those needs were a true emergency. The ISOs would notify Western that assistance may be necessary within a 24-hour period, but the timing and duration of assistance were often not specified. When the need for additional energy became apparent, Western notified Reclamation to immediately begin increasing releases at Glen Canyon Dam sufficient to control the potential brown-out conditions. This service has been offered to all electric utilities within the region under the same criteria.

An example of how releases from Glen Canyon Dam were altered to accommodate power generation needs during the California energy crisis is illustrated in Figure 11. This figure illustrates how daily fluctuation and upramp rate restrictions imposed by the 1996 ROD were suspended in order to meet power generation needs by showing the scheduled release (dashed line) and the actual releases (solid line) from the dam on May 7-8, 2001. Note that both power requests were received in the late afternoon when power needs typically increase and then were canceled in late evening when the demand for power decreased. Reclamation was allowed to increase flows higher than the 5,000 to 8,000 cfs maximum daily fluctuation and faster than the 4,000 cfs/hr maximum upramp rate since these emergencies were deemed Stage III electrical emergencies. Daily fluctuations to meet emergency power generation were on occasion as high as 14,650 cfs/day and were made with upramp rates as high as 8,280 cfs/hr. Peak daily releases during emergency releases remained below the maximum 25,000 cfs guideline, and operators at Glen Canyon Dam followed the 1,500 cfs/hr guideline for downramping rates. A detailed day-by-day description of the actions taken by Western to assist the California ISOs to meet the power needs of their customers during the California energy crisis of 2000-2001 can be found in Appendix B.

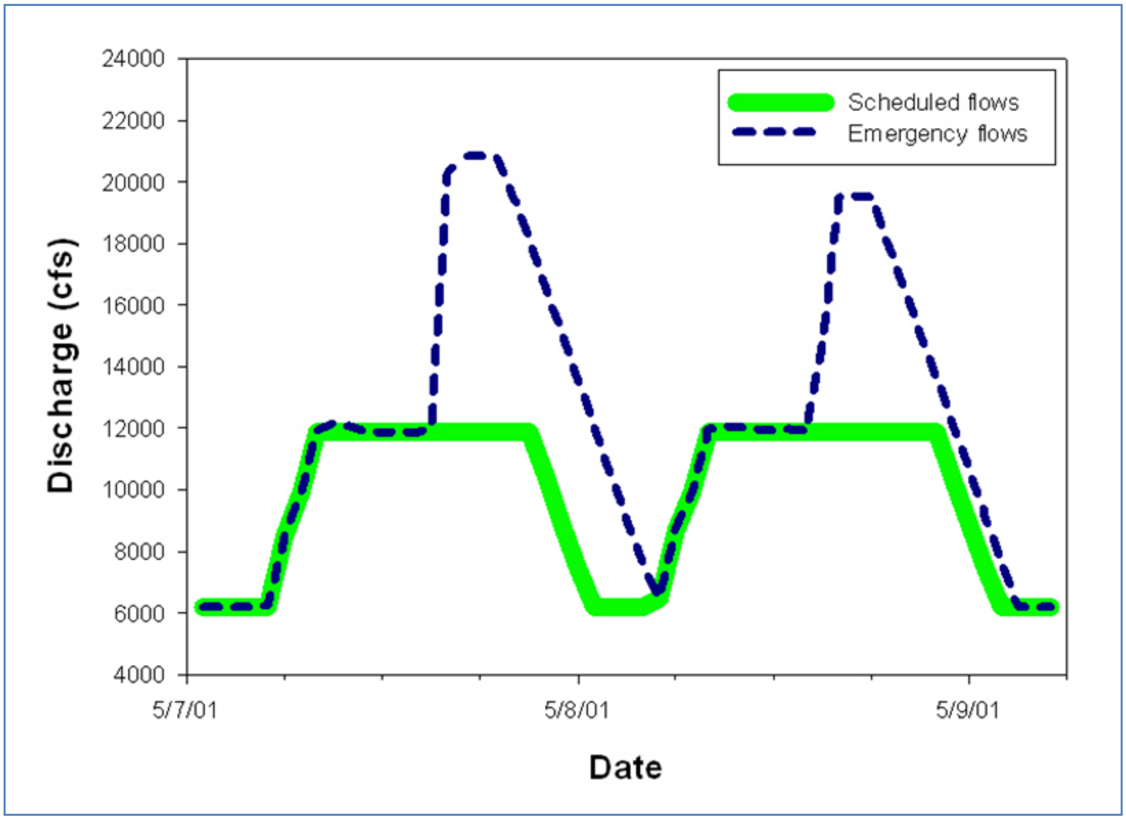

Figure 11. The scheduled release (solid line) and the actual releases (dashed line) from Glen Canyon Dam on 7-8 May 2001 to meet two Stage III power emergency requests from the California Independent System Operators.

Decision Process for a Rapid Response HFE

The decision process for a rapid response HFE would need to be implemented within a matter of hours of the first indication of a Paria River flood. Information indicating an increase in dam release was being considered would need to be transmitted quickly to Western's dispatch center (Energy Management and Marketing Office) and to operators at Glen Canyon Dam.

Prior to the first test of a rapid response HFE, the following would need to be developed:

- A standard operating procedure (SOP) would have to be prepared that would be followed by Western and Reclamation operators.
- An interagency agreement between Western and Reclamation regarding the SOP referred to above would need to be signed.
- An agreement with one or more electrical utilities to take the electrical energy produced by a rapid response HFE would need to be developed.

Scientifically Developed Triggers

The establishment of a clear set of scientifically based triggering criteria for the implementation of a rapid response HFE is critical to the success of the protocol. The 2002 EA (Reclamation 2002) identified a flow of at least 2,500 cfs from the Paria River is necessary to provide the minimum sediment input to consider implementing an HFE. If this criterion had been in place in 2010, three rapid response HFEs could have been implemented. To trigger a rapid response HFE, additional criteria such as rate of increasing flow, magnitude of peak flow, and duration of flood at one or more upstream gages could be used (Figure 12). Other data such as additional streamgage data, weather radar, storm total, and 1-hour precipitation totals could also be used to further refine HFE triggering criteria.

Stage Changes at Lees Ferry

Present operations result in daily fluctuations in river stage as more or less water is released for power production. During normal operations, (e.g., in an 800,000 AF month such as August), the daily stage change at Lees Ferry is about 1.9 ft. This is due to the daily fluctuation between the nighttime flow of 8,600 cfs and the daytime flow of 16,800 cfs. The maximum rate at which the river stage changes at Lees Ferry is approximately 1.3 ft/hr and is limited by the current upramp rate of 4,000 cfs/hr. The potential stage change during a rapid response HFE would vary depending on whether it is initiated during nighttime or daytime flows. For example, a rapid response HFE in August would increase the stage at Lees Ferry by 4.1 ft if initiated during nighttime flows (8,600 cfs to 31,000 cfs), but would increase by only 2.2 ft if initiated during daytime flows (16,800 cfs to 31,000 cfs).

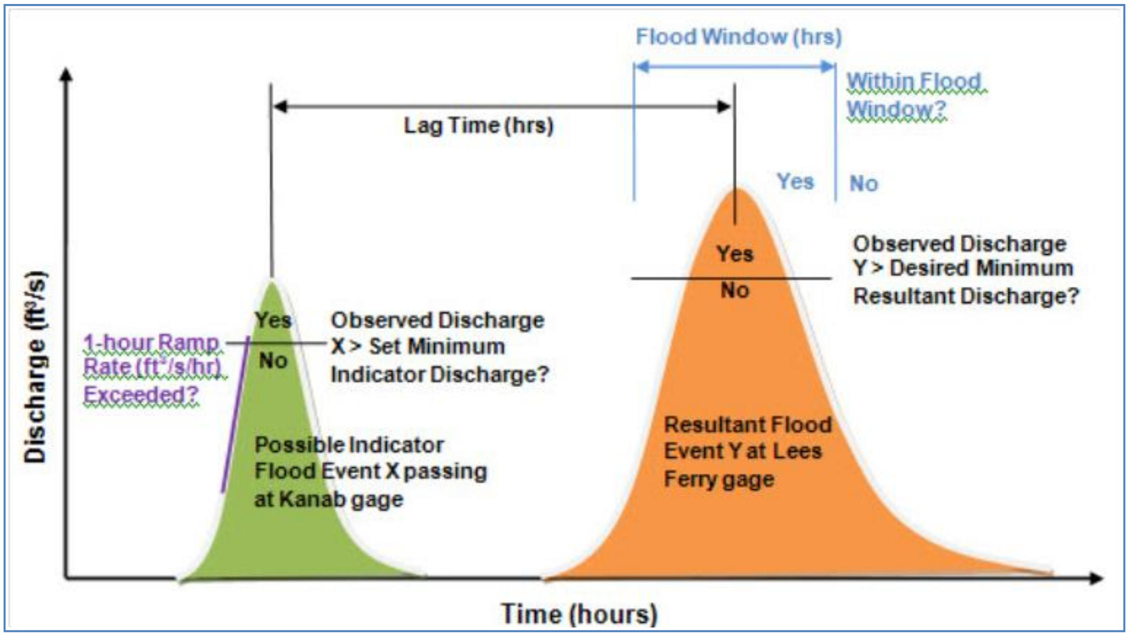

Figure 12. A conceptual diagram presented by Kimbrel (2012) for screening an indicator flood for potential rapid response HFE. Triggers identified to begin releases at Glen Canyon Dam to match an indicator flood at the Kanab gage include reaching a minimum discharge and exceeding a specified 1-hour ramp rate. Triggers to continue HFE releases at Glen Canyon Dam include a resultant flood of a certain minimum discharge reaching Lees Ferry within a certain flood window.

Effect of Up-ramp Rates

Ramping rates at Glen Canyon Dam can affect the rate of increasing or decreasing flow at Lees Ferry and at sites utilized for recreation (Figure 13). A review of operations at Glen Canyon Dam using a water routing model showed that flows at Lees Ferry do not appear to increase at the same rate as at Glen Canyon Dam. For example, when the powerplant utilized upramp rates of 7,000 cfs/hr during the first week of July 1991, the maximum resultant flow increase at Lees Ferry was only 4,500 cfs/hr. When upramp rates were increased to 10,750 cfs/hr during operations in August 1986, the maximum resultant flow increase at Lees Ferry only increased to 4,700 cfs/hr (USGS gage # 09382000).

The CRFSS Graphical Users Interfaces (Korman *et al.* 2004) was used to model flow responses at Lees Ferry to ramping rates at Glen Canyon Dam ranging from 4,000 to 26,000 cfs/hr with flows starting at a base flow of 5,000 cfs and continuing to the maximum powerplant capacity of 31,000 cfs (Figure 13). The model indicated ramp rates from 4,000 to 9,000 cfs/hr have a near linear, but not a 1:1 relationship with the flow rate at Lees Ferry. For ramp rates between 9,000 and 11,000 cfs/hr, there appears to be little change in the rate of increasing flow at Lees Ferry. In order to minimize impacts to resources below the dam while allowing maximum flow rate increases at Lees Ferry, the CRFSS model indicated that ramp rates for a rapid response HFE should be limited to no more than 9,000 cfs/hr.

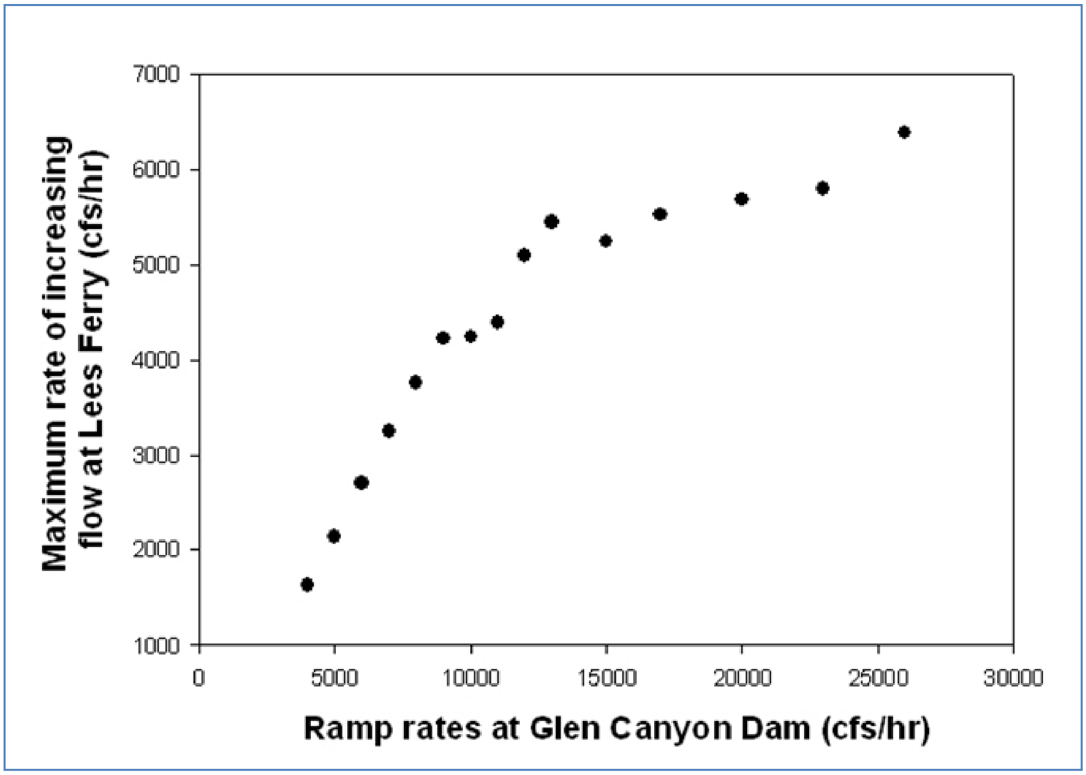

Figure 13. Modeled flow responses at Lees Ferry to ramping rates at Glen Canyon Dam ranging from 4,000 to 26,000 cfs/hr. Modeled flows started at a base flow of 5,000 cfs and continuing with the specified ramp rate to the maximum powerplant capacity of 31,000 cfs.

Required Ramping Rates for a Rapid Response HFE

The Colorado River Flow, Stage and Sediment (CRFSS) Graphical Users Interfaces (Korman *et al.* 2004) model was also used to determine which ramp rates would allow powerplant capacity flows to reach Lees Ferry within the 7 to 9 hour window identified by Kimbrel (2012) of an impending Paria River flood. Flows at Lees Ferry were modeled with ramp rates from Glen Canyon Dam of 4,000; 5,000; and 6,000 cfs/hr at a daily minimum release of 8,800 cfs and a daily maximum of 16,800 cfs. These releases were chosen to simulate a typical August release schedule when a Paria River flood is most likely to occur. The typical monthly release for August under MLFF in a minimum release year is approximately 800,000 AF and the targeted operations have daily minimum flows of 8,800 cfs and daily maximum flows of 16,800 cfs. The model suggested that when the release began at the daily maximum of 16,800 cfs, flows at Lees Ferry would reach 99% of the peak powerplant capacity flow within 7 hours at all three test ramp rates (Figure 14a). If the release began at the daily minimum of 8,800 cfs, flows at Lees Ferry reached 88%, 96% and 99% of the powerplant capacity, within 7 hours of release at Glen Canyon Dam with 4,000; 5,000 and 6,000 cfs/hr ramp rates, respectively (Figure 14b). By 9 hours after beginning the ramp up at Glen Canyon Dam, flows at Lees Ferry would reach 99% of powerplant capacity for all three ramp rates regardless of whether the release began at the daily maximum or minimum. The rapid response HFE proposed by Western in September 2010 suggested upramp rates of 4,000 cfs/hr as specified in the 1996 ROD (Reclamation 1996).

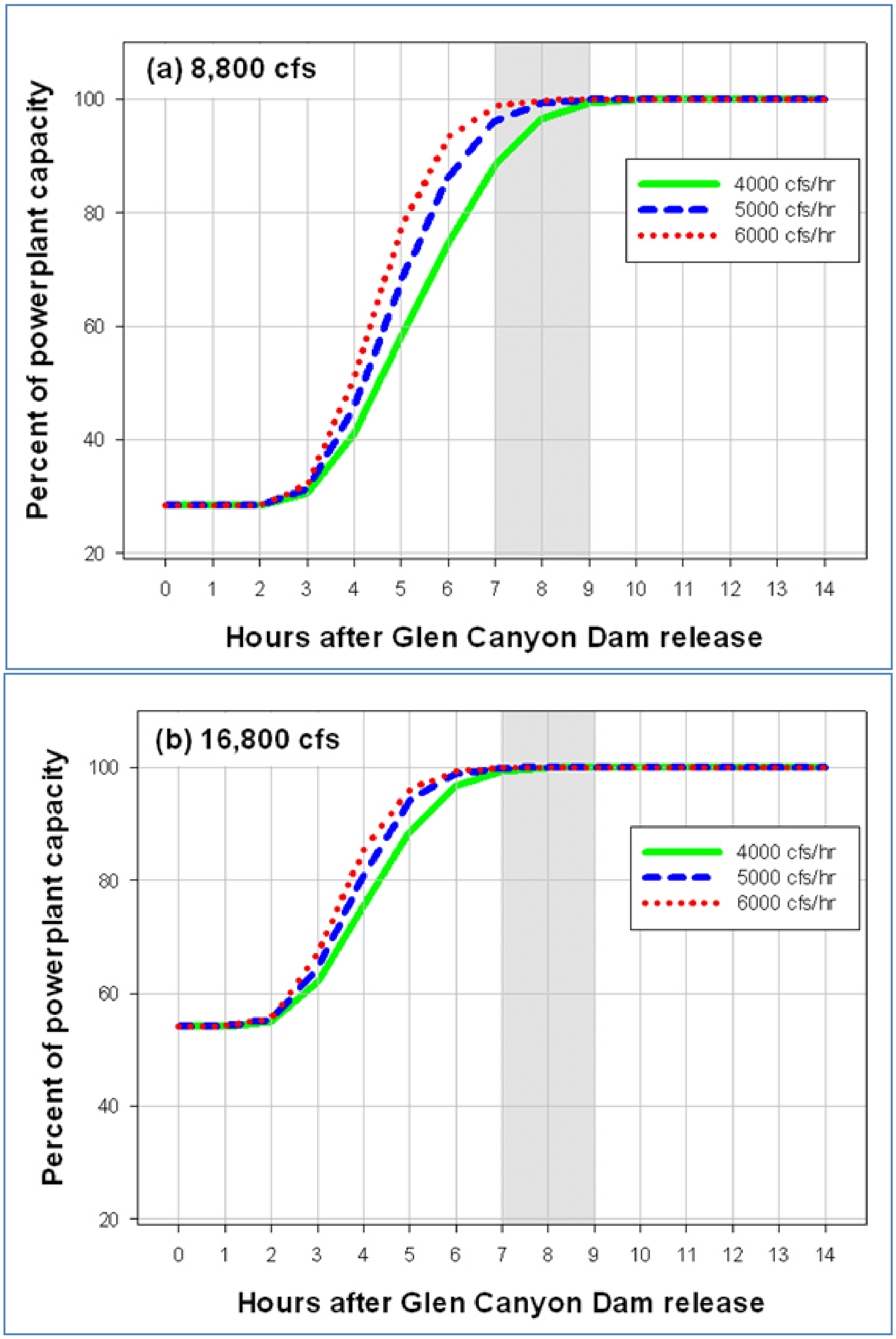

Figure 14. Modeled flows at Lees Ferry in response to Glen Canyon Dam upramp rates of 4,000; 5,000; and 6,000 cfs/hr from a base flow of (a) 8,800 cfs and (b) 16,800 cfs to powerplant capacity (31,000 cfs) showing powerplant capacity flows reach Lees Ferry within the 7 to 9 hour time window of notification for an impending Paria River flood identified by Kimbrel (2012). These

values were selected because they are the most likely daytime and nighttime minimum releases for the month of August.

SAFETY AND OTHER CONSIDERATIONS FOR RAPID RESPONSE

A rapid response HFE would time dam releases to coincide with substantial Paria River floods in order to utilize inputs before they are transported downstream into Lake Mead. Thus, the decision to implement this type of HFE would have to be done quickly with established protocols to ensure safety to recreational users, to protect private property, and to ensure that the power system is not adversely affected. Prior to the initiation of a rapid response HFE, an appropriate warning system would need to be developed. An effective warning system will require coordination with dam operators and notices to anglers, boaters, rafters, and recreationists to ensure public safety.

Safety Considerations Before and After 1996 ROD Flows

Operations before implementation of the 1996 ROD included little consideration for safety issues for river users. Operations included unconstrained changes in flow rates that often ranged within a day from about 1,000 cfs to near the maximum powerplant capacity of 33,000 cfs. Generally, flow fluctuations peaked twice each day to follow electrical demand. Unrestricted ramping rates allowed Glen Canyon Dam to follow power loads in the CRSP Power Area. Changes in river stage at Lees Ferry initially ranged up to 5 ft/day and often exceeded 6 ft/day by the early 1970’s. In the mid-1970’s, minimum flows were increased from 1,000 cfs to 3,000 cfs during the summer months (Memorial Day to Labor Day) to accommodate the National Park Service and river running organizations. This modification to minimum flows was one of the first accommodations to improve passage through downstream rapids that were previously impassable at low flows.

With the implementation of the 1996 ROD, daily changes in river stage have been reduced to less than 2.5 ft/day. However, during the 2000-2001 California energy crisis mentioned previously, flow fluctuations were increased to as high as 5.8 ft/day with a peak rate of stage change of 2.6 ft/hr. To accommodate these changes from normal operations, the downstream recreational community in the Grand Canyon was notified by Western, Reclamation, and the National Park Service of the higher flows and faster ramping rates. During each of the seven periods of assistance, Reclamation’s regional office was notified of pending flow changes by Western’s office in Montrose, CO. Reclamation then contacted the river users’ community by phone at the onset of each event. To the extent possible, commercial float trips in the canyon were also notified by river guide representatives via satellite phone. The National Park Service likewise notified people camping in Glen Canyon of the potential for impending changes in flow and stage by dispatching a Park Service boat from Lees Ferry (Jeff English, personal communication). These actions were deemed sufficient to satisfy downstream safety concerns resulting from these operational changes.

The Kinematic Wave Phenomenon

One concern with the implementation of either HFE protocol is the potential for creating large kinematic waves that increase the erosion of existing sediment in the canyon. A kinematic wave is generated by the force of gravity on the water flowing down the canyon following an increase in flow. This is problematic because the kinematic wave travels downstream faster than the actual water producing the flood; up to twice as fast depending on river morphology. For example, if a rapid response HFE release from Glen Canyon Dam of 31,000 cfs is timed to arrive at Lees Ferry (river mile 0) at the exact same time a flood emerges from the Paria River, a kinematic wave will be pushed out in front of the sediment-laden flood waters as the flood progresses downstream. This kinematic wave would reach the Little Colorado River (river mile 61.7) approximately 7.9 hours before the arrival of sediment-laden water from the Paria River (J. Schmitt, pers. comm.). The increase in stage and velocity associated with the kinematic wave has the potential to increase the erosion of existing sediment in the canyon until the arrival of the sediment-laden flood waters.

The effects of the kinematic wave could possibly be mitigated by allowing the sediment-laden flood waters from a Paria River flood to travel downstream sufficiently so the wave does not erode existing sediment in a targeted reach of the canyon without there being new sediment present in the water column to replace it. A potential advantage of the rapid response HFE is that its timing could be timed so the resultant kinematic wave arrives in a targeted reach of the river shortly after the arrival of the first sediment-laden flood waters from the Paria River thereby reducing the net loss of sediment from that reach of the river. This alternative strategy would require further modeling to better understand how a rapid response HFE transports fine and course sediment present in the water column and how to time an HFE to avoid a kinematic wave moving through a critical reach of the river under clear-water conditions. Additional study of kinematic waves is needed to better identify the impacts they have on existing sediment and whether this is an issue that needs to be mitigated by alternative flow scenarios.

Next Steps

This paper is intended to provide information to stakeholders in the Glen Canyon Dam Adaptive Management Group on the feasibility of conducting a rapid response HFE in concert with a flood from the Paria River. The scope of this paper was limited to an analysis of whether one could anticipate floods from the Paria River with reasonable certainty and determine if operators at Glen Canyon Dam could increase releases in a timely manner to match that flood when it reached the Colorado River. This paper also describes past changes to normal operations at Glen Canyon Dam to accommodate such things as emergency releases and how power and safety issues were dealt with during those situations. In summary, this paper:

- Identifies the Paria River as the single largest contributor of sand, silt, and clay to the Colorado River below Glen Canyon Dam with large sediment input events occurring during summer and fall monsoonal storms which peak in August;
- Outlines how notification of an impending flood in the Paria River can be obtained using a combination of upstream river gages, rain gages, and weather radar to predict a flood of a certain magnitude reaching the Colorado River;

- Identifies that monitoring upstream river gages allows enough warning (7 to 9 hours) to allow operators at Glen Canyon Dam to match powerplant capacity flows with a flood from the Paria River at Lees Ferry using ROD upramp rates (4,000 cfs/hr); and
- Provides examples of past events that demonstrate operations at Glen Canyon Dam can respond to a change from normal operations to something like a rapid response HFE without creating any fundamental safety or operational issues.

We recognize that there are several critical items that need to be determined or developed before a rapid response HFE can be implemented. These include:

- A determination if additional NEPA compliance is needed to:
    - Implement a rapid response HFE outside the October-November HFE window identified in the HFE EA,
    - Identify how Reclamation will provide the tribes with a 30-day notice of an impending HFE if its timing is dependent on a stochastic variable such as a flood in the Paria River,
- The development of a science plan to:
    - Compare the effects of a rapid response HFE with the effects of a store and release HFE,
    - Determine effects on downstream resources (i.e. humpback chub, sediment, trout, foodbase), and
    - Determine the effects of kinematic waves on downstream sediment resources and if there is a way to adjust the timing of the HFE release from Glen Canyon Dam to mitigate any negative effect.
- Identify triggers (flow-based or sediment-based) that would be used to initiate an HFE release from Glen Canyon Dam,
- Develop a real-time monitoring method for sediment inputs from the Paria River that could be used to determine when to end an HFE,
- Develop a safety plan to notify downstream users (anglers, campers, river runners, science community) of an impending HFE,
- Develop an agreement between Western and Reclamation that outlines standard operating procedures to be followed during a rapid response HFE, and
- Identify an electrical utility tied to Western’s electrical system that will agree to take the power generated during the HFE.

LITERATURE CITED

Kimbrel, S. 2012. Determining large flood events on the Paria River for a rapid response alternative high flow experiment. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center Denver, Colorado. Technical Report No. SRH-2012-08. 25 pgs.

Korman, J., J. Buszowski, S. Wiele, T. Randle, T. Melis, D. Topping. 2004. Colorado River Flow, Stage and Sediment Model, Version 2.02. http://www.mountainsoft.net/index.html. Accessed on 2/15/12.

Lucchitta I., L.B. Leopold. 1999. Floods and sandbars in the Grand Canyon. GSA Today 9(4):1-7.

Melis, T. S., ed. 2011. Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona: U.S. Geological Survey Circular 1366, 147 p. Reclamation. 1995. Operation of Glen Canyon Dam—Final Environmental Impact Statement, Colorado River Storage Project, Coconino County, Arizona: Salt Lake City, Utah, Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf.

Reclamation. 1996. Final environmental assessment and finding of no significant impact, Glen Canyon Dam beach/habitat-building test flow, spring 1996. Bureau of Reclamation, Salt Lake City, Utah.

Reclamation. 2002. Final environmental assessment and finding of no significant impact, proposed experimental releases from Glen Canyon Dam and removal of non-native fish, 2003-2006. Bureau of Reclamation, Salt Lake City, Utah.

Reclamation. 2011. Environmental Assessment—Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020. Bureau of Reclamation, Upper Colorado Region, December 30.

Rubin, D. M., D. J. Topping, J. C. Schmidt, J. Hazel, M. Kaplinski, and T. S. Melis. 2002. Recent sediment studies refute Glen Canyon Dam hypothesis. Transactions American Geophysical Union 83(25):277-278.

Topping, D.J. 1997. Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona, Ph.D. thesis, 406 pp., Univ. of Wash., Seattle, Washington.

APPENDIX A – NATIONAL WEATHER SERVICE WEATHER STATION WEBSITES

Cedar City, UT:
http://forecast.weather.gov/MapClick.php?map.x=135&map.y=323&minlon=115.5&maxlon=108.5&minlat=36.96&maxlat=42.68&mapwidth=354&site=slc&zmx=1&zmy=1

http://www.wunderground.com/cgi-bin/findweather/getForecast?query=84720

Bryce Canyon, UT:
http://forecast.weather.gov/MapClick.php?map.x=168&map.y=340&minlon=-115.5&maxlon=108.5&minlat=36.96&maxlat=42.68&mapwidth=354&site=slc&zmx=1&zmy=1

http://www.wunderground.com/cgibin/findweather/getForecast?query=Bryce+Canyon+National+Park%2C+Utah

Page, AZ:
http://www.wunderground.com/cgi-bin/findweather/hdfForecast?query=86040

Kanab, UT:
http://www.wunderground.com/cgibin/findweather/hdfForecast?query=86040

APPENDIX B – ACTIONS TAKEN BY WESTERN DURING THE CALIFORNIA ENERGY CRISIS

The following is a day-by-day description of actions taken by Western to assist the California ISOs to meet the power needs of their customers during the California energy crisis of 2000-2001.

September 18, 2000: Power demands in California exceeded the available power supplied by the ISOs including all requests for power outside the immediate control area. As a result, Western increased electrical generation at Glen Canyon Dam from 325 MW to 655 MW. Releases from Glen Canyon Dam increased from 8,190 cfs to 15,780 cfs (+7,590 cfs) over the space of one hour to meet this generation need. The magnitude of increased generation from Glen Canyon Dam was only limited by available transmission capacity into California. The duration of this emergency release was about four hours, after which releases were reduced by the 1,500 cfs/hour downramp rate.

February 15, 2001: The Glen Canyon Dam Powerplant responded to another Stage III power emergency in California. Releases from the dam increased 5,320 cfs between 1200 and 1300 hours to meet the generation demand for the emergency. Releases of approximately 20,000 cfs were made throughout the afternoon as emergency assistance continued. Late in the afternoon (approximately 1900 hours), a 1,500 cfs/hr downramp was initiated and maintained until pre-scheduled releases of 8,500 cfs were reached in the early morning hours of February 16, 2001. The 19,950 cfs release was about 5,000 cfs above the pre-scheduled peak release for the day and approximately 11,550 cfs above the daily minimum.

March 19-20, 2001: The Glen Canyon Dam Powerplant increased generation by about 300 MW above its scheduled power output in response to another Stage III power emergency. On 19 March, the response occurred at 1100 hours and lasted until 1900 hours. Releases from Glen Canyon Dam increased 6,690 cfs between 1000 and 1200 hours and peaked at approximately 21,000 cfs between 1800 and 2000 hours. Peak flows were 7,590 cfs over the scheduled maximum daily release of 13,500 cfs and 13,870 cfs over the daily minimum flow. On 20 March, the response occurred at 1500 hours and lasted until 1900 hours. Releases from Glen Canyon Dam increased 6,720 cfs between 1400 and 1500 hours and peaked at approximately 20,000 cfs between 1800 and 2000 hours. Peak flows were 6,700 cfs over the pre-scheduled maximum daily release of 13,500 cfs and 12,130 cfs over the daily minimum flow.

May 7-8, 2001: The Glen Canyon Dam Powerplant delivered 5,284 MWH into California in response to another Stage III power emergency. Water released with this delivery totaled approximately 11,163 AF. The maximum power delivery to California occurred on May 7 from 1600 to 1900 hours at 350 MW. Peak releases from the dam during this time were 20,830 cfs which was 8,930 cfs above the scheduled release of 11,900 cfs. Ramping rates between 1500 and 1600 hours were approximately 8,280 cfs/hr which was above the 4,000 cfs/hr maximum ramping specified by the 1996 ROD. The peak flow was 14,650 cfs above the daily minimum flow which also exceed the maximum daily fluctuation rate limit of 6,000 cfs set by the 1996 ROD. The additional energy delivered was paid back by the California ISOs by allowing for the reduction of on-peak generation at Glen Canyon Dam by approximately 100 MW (approximately 2,400 cfs) from pre-scheduled generation between May 14 and May 17.

May 31, 2001: The Glen Canyon Dam Powerplant responded to its last Stage III power emergency. Generation was increased by about 135 MW above the pre-scheduled level for the day. This response occurred at about 1400 hours with an upramping rate of 3,020 cfs/hr and continued until 1800 hours. Peak releases reached 16,050 cfs which was 3,350 cfs over the prescheduled maximum daily release.