United States Department of the Interior

BUREAU OF RECLAMATION
P.O. Box 25007
Denver, CO 80225-0007

IN REPLY REFER TO:

86-68240
RES-3.20

VIA ELECTRONIC MAIL

MEMORANDUM

To: Regional Director, Salt Lake City, Utah
Attn: UC-370 (Kubly)

From: Sean Kimbrel
Hydraulic Engineer, Sedimentation & River Hydraulics Group

Subject: Determining Large Flood Events on the Paria River for a Rapid Response Alternative High Flow Experiment – Colorado River Storage Project, Glen Canyon Dam, Arizona – Upper Colorado Region

At the request of Bureau of Reclamation's Upper Colorado Regional Office, analyses were performed on the Paria River by Reclamation's Technical Service Center to evaluate an alternative High Flow Experiment (HFE) protocol for Glen Canyon Dam operations, proposed by the Western Area Power Administration. The alternative HFE proposes to coordinate controlled releases from Glen Canyon Dam with sediment-rich flood events in the Paria River. One goal of the coordinated releases is to increase the ecological benefits downstream of Glen Canyon Dam through Marble Canyon.

As part of the evaluation process, this study investigated various types of water and sediment related data sources to determine the feasibility of predicting the occurrence of a large flood event in the Paria River. As a surrogate for continuous sediment data, continuous hydraulic discharge data from two different U.S. Geological Survey (Survey) gages in the Paria River Basin were statistically analyzed to determine if a relationship between the upstream Survey discharge gage near Kanab, Utah, (Kanab gage) and the downstream Survey discharge gage at Lees Ferry, Arizona, (Lees Ferry gage) could be developed to predict large flood events. The Kanab gage is identified as the indicator gage and the Lees Ferry gage is designated as the resultant gage. This report documents the steps taken to determine the relationship between the two gages, and the threshold magnitude of resultant flood events that could be statistically predicted at the Lees Ferry gage.

The analyses presented in this document do not address any of the sediment processes that will occur in the Colorado River if a HFE is coordinated with a flood in the Paria River. There are several important sediment related issues that will be important to the benefits that would result from this action. One important consideration is that the sediment concentration, storage, and river bed evolution are not perfectly correlated with flow discharge. There will be hysteresis in the relationship between sediment concentration and flow discharge meaning that sediment concentration is not only dependent upon the current discharge, but also on the flow history. Also, the sediment available for transport near the confluence of the Paria River and Colorado River will be a complex function of flow history of not only the Paria River, but also the Colorado River. Therefore, the instantaneous flow in the Paria may be insufficient information to determine the timing and magnitude of a HFE.

The analyses presented here only address the hydrologic issues associated with coordinating HFE with flood flows from the Paria.

The study was completed by Sean Kimbrel, and was peer reviewed by Blair Greimann and Kendra Russell, all with the Sedimentation and River Hydraulics Group. If you have questions related to this study, please contact me at 303-445-2539 or email at skimbrel@usbr.gov.

Attachment

cc: National Park Service – NRSS WRD – Water Rights Branch, 1201 Oakridge Drive, Fort Collins, CO 80525
Attn: (Wondzell)
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(w/att to ea)

86-68200 (Reading File)
86-68240 (Kimbrel, Russell, Greimann, File)
UC-435 (Clayton)
UC-436 (Hermansen)
(w/att to ea)

RECLAMATION
Managing Water in the West

Technical Report No. SRH-2012-08

Determining Large Flood Events on the Paria River for a Rapid Response Alternative High Flow Experiment

Colorado River Storage Project
Glen Canyon Dam, Arizona
Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

March 2012

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Technical Service Center
Denver, Colorado

March 2012

Peer Review Certification: This document has been peer reviewed and is believed to be in accordance with the service agreement and standards of the profession.

PREPARED BY:

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Acronyms

AZ	Arizona
HFE	High Flow Experiment
NCDC	National Climate Database Center
NOAA	National Oceanic and Atmospheric Administration
Reclamation	Bureau of Reclamation
TSC	Technical Service Center (Reclamation)
UC	Upper Colorado Regional Office (Reclamation)
USGS	U.S. Geological Survey
UT	Utah
VBA	Visual Basic
WAPA	Western Area Power Administration

Determining Large Flood Events on the Paria River for a Rapid Response Alternative High Flow Experiment

I. Introduction

At the request of Bureau of Reclamation's (Reclamation) Upper Colorado (UC) Regional Office, analyses were performed on the Paria River by Reclamation's Technical Service Center (TSC) to evaluate an alternative High Flow Experiment (HFE) protocol for Glen Canyon Dam operations, proposed by the Western Area Power Administration (WAPA). The alternative HFE proposes to coordinate controlled releases from Glen Canyon Dam with sediment-rich flood events in the Paria River. One goal of the coordinated releases is to increase the ecological benefits downstream of Glen Canyon Dam through Marble Canyon.

As part of the evaluation process, this study investigated various types of water and sediment related data sources to determine the feasibility of predicting the occurrence of a large flood event in the Paria River. As a surrogate for continuous sediment data, continuous hydraulic discharge data from two different United States Geological Survey (USGS) gages in the Paria River Basin were statistically analyzed to determine if a relationship between the upstream USGS discharge gage near Kanab (Kanab gage), Utah (UT), and the downstream USGS discharge gage at Lees Ferry (Lees Ferry gage), Arizona (AZ), could be developed to predict large flood events. The Kanab gage is identified as the indicator gage and the Lees Ferry gage is designated as the resultant gage. This report documents the steps taken to determine the relationship between the two gages, and the threshold magnitude of resultant flood events that could be statistically predicted at the Lees Ferry gage.

The analyses presented in this document do not address any of the sediment processes that will occur in the Colorado River if a HFE is coordinated with a flood in the Paria River. There are several important sediment related issues that will be important to the benefits that would result from this action. One important consideration is that the sediment concentration, storage, and river bed evolution are not perfectly correlated with flow discharge. There will be hysteresis in the relationship between sediment concentration and flow discharge meaning that sediment concentration is not only dependent upon the current discharge, but also on the flow history. Also, the sediment available for transport near the confluence of the Paria and Colorado River will be a complex function of flow history of not only the Paria, but also the Colorado River. Therefore, the instantaneous flow in the Paria may be insufficient information to determine the timing and magnitude of a HFE.

The analyses presented here only address the hydrologic issues associated with coordinating HFE with flood flows from the Paria.

A. Background and Data Sources

A previous analysis of the Paria River was performed in David Topping's dissertation (Topping, 1997) addressing the physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flood events on the Paria River. Some key background information from (Topping, 1997) that is relevant and applicable to this alternative HFE study is summarized in the proceeding sub-sections.

1. Hydrology

The Paria River is an ephemeral river, with infrequent large floods of very short duration (Topping, 1997, p. 64). In Topping's study, discharge data were compiled and corrected at 3 different gage sites from 1923 to 1996. The three USGS gage sites were below Cannonville, UT (no. 09381500), near Kanab, UT (no. 09381800), and above the confluence with the Colorado River at Lees Ferry, AZ (station no. 09382000). Several statistical analyses were performed with the discharge records. Throughout the period of record, no statistically significant trends were found pertaining to a change in peak discharge, flood volume, or flood duration (Topping, 1997, p. 65).The bankfull discharge at all 3 sites was determined to be 90 m^3/s or 3,178 ft^3/s (Topping, 1997, pp. 6, 38), occurring approximately every 2.2 years (Topping, 1997, p. 65). Most floods events are suspected to be caused by intense summer precipitation events in the uppermost 14% of the basin, near and upstream of the Cannonville, UT discharge gage (Topping, 1997, p. 60). Floods along the length of Paria River were determined to be conveyed with little modification/attenuation. For the period of record, flood peaks decrease by less than 33% from Cannonville to Lees Ferry, and may increase by 300% (Topping, 1997, pp. 60-64).

A flood frequency curve was presented in Topping's study (Topping, 1997, p. 62) showing the peak flood discharge as a function of return period for the Paria River at Lees Ferry, AZ, which includes the period of record from 11/22/1923 to 9/30/1996. Approximate values from this flood frequency curve were copied and are presented below in Table 1.

Table 1. – Approximate Flood Frequency Results of Paria River at Lees Ferry (Topping, 1997; p. 62)

Return Period (year)	Peak Discharge (m^3/s)	Peak Discharge (ft^3/s)
2	75	2,649
Bankfull (~2.2)	90	3,178
5	140	4,944
10	170	6,003
20	205	7,240
50	280	9,888
100	305	10,771

As described in Topping's study, the Paria River has infrequent floods of very short duration. To show this short duration or "flashy" response in the hydrograph, Figure 1 presents an example hydrograph taken from the Lees Ferry gage. The flood hydrograph shows that the example flood event begins and ends within a 24 hour period.

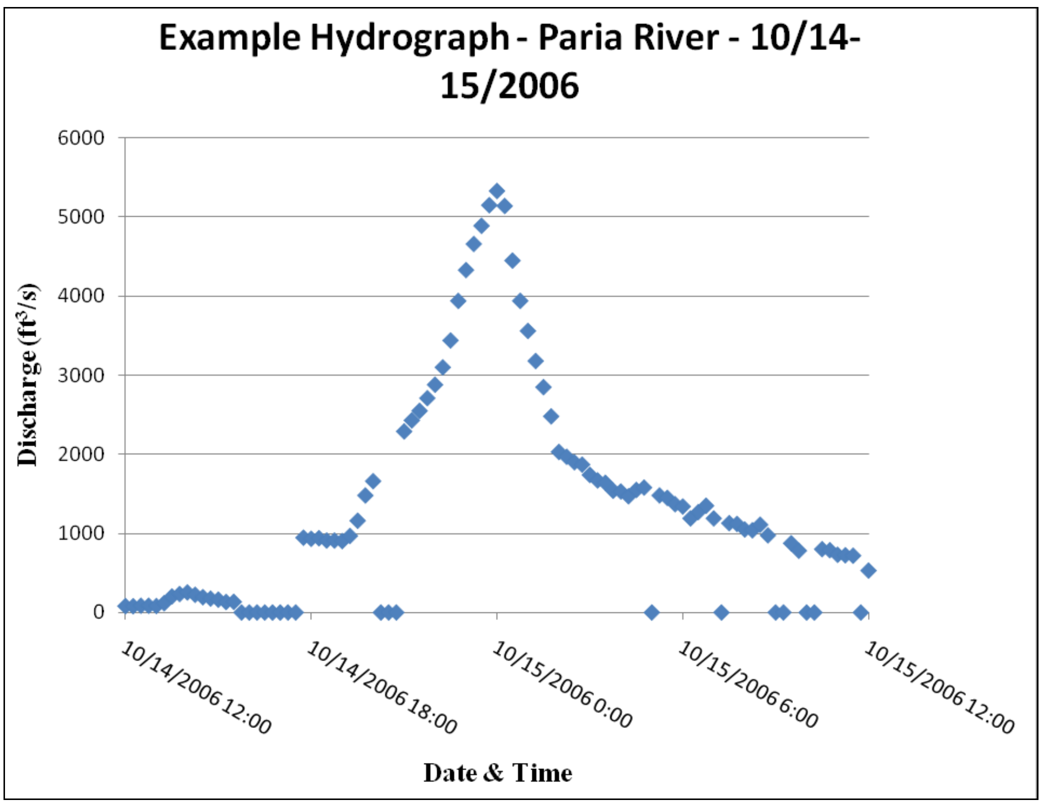

Figure 1. – Example Flood Hydrograph of Paria River at Lees Ferry, AZ (USGS station no. 09382000) Gage.

In Topping's study, statistics show that the bankfull discharge occurs every 2.2 years, but is equaled or exceeded only 0.021% of the time (Topping, 1997, p.58). Large floods with discharges greater than bankfull discharge (~3,178 ft^3/s) are rare and the flow duration is short (mean of 3.66 hours, Topping, 1997, p. 53).

2. Sediment

As part of Topping's dissertation, multiple sites were investigated along the Paria River, predominately in the Lees Ferry reach and also near the Cannonville, UT gage. Local incision of the channel was observed to be occurring in Lees Ferry Reach since the closure of Glen Canyon Dam. In addition, the biggest physical changes in the Paria Basin is botanical, with the introduction of Tamarisk and Russian olive along the riparian corridor.

The Paria River has one of the longest term suspended-sediment records in the world for a river of its type and size (Topping, 1997, p. 207). From 10/1/1947 through 9/30/1976, quasi-daily samples of suspended sediment data were collected in the Lees Ferry, AZ reach and analyzed for concentration. From 7/7/1954 through 9/26/1976, 145 of these samples were collected and analyzed for both concentration and grain-size distribution (Topping, 1997, p. 207).

In Topping's study, statistical analyses of the suspended-sediment records revealed little significance in the changes in sediment storage or in the sediment grain size distribution along the Paria River over the period of record. Based on statistical analyses of the suspended-sediment record, several statistically significant factors were determined, however: (1) Suspended sand volume concentration is higher after a smaller flood peak (<28.3 m^3/s or 1,000 ft^3/s) than the suspended sand volume concentration after a larger discharge flood peak (Topping, 1997, p. 217), (2) the suspended silt-clay concentration during the monsoon season (July 1 – Oct 31) is enhanced relative to the suspended silt-clay concentration during non-monsoon seasons (Topping, 1997, p. 217), and (3) the suspended silt and clay concentration decays with time (>100 hrs) after a flood event during the monsoon season. Topping's sediment transport analyses determined that the sand size fractions determine the geomorphology of the Paria River, where gravels size fractions are not mobilized until extreme floods, and silt-clay sized particles are advected through the system. Inferences of the significance in the suspended sand volume concentrations with the timing of smaller versus larger flood peaks indicate that the smaller peaks replenish sand on the channel bed, and larger peaks deplete the amount of sand on the channel bed. The enhancement of silt-clay fractions during monsoonal periods was caused by intense monsoonal rainfall events eroding hillslopes in the upper basin, whereas snowmelt or rain-on-snow events caused less erosion.

3. Discharge

For this study, the two lower discharge gages currently active in the Paria River basin were used. The upstream gage is the Paria River near Kanab, UT (09381800) gage. Continuous discharge data is available at this gage from 9/17/2002 to present. The downstream discharge gage is the Paria River at Lees Ferry, AZ (09382000) gage. Continuous discharge data is available at this gage from 10/16/1982 to present. The overlapping period of record between these two discharge gages is compared in this study, which is from 9/17/2002 to near present (8/25/2010). Figure 2 presents a location map of the USGS discharge gages on the Paria River.

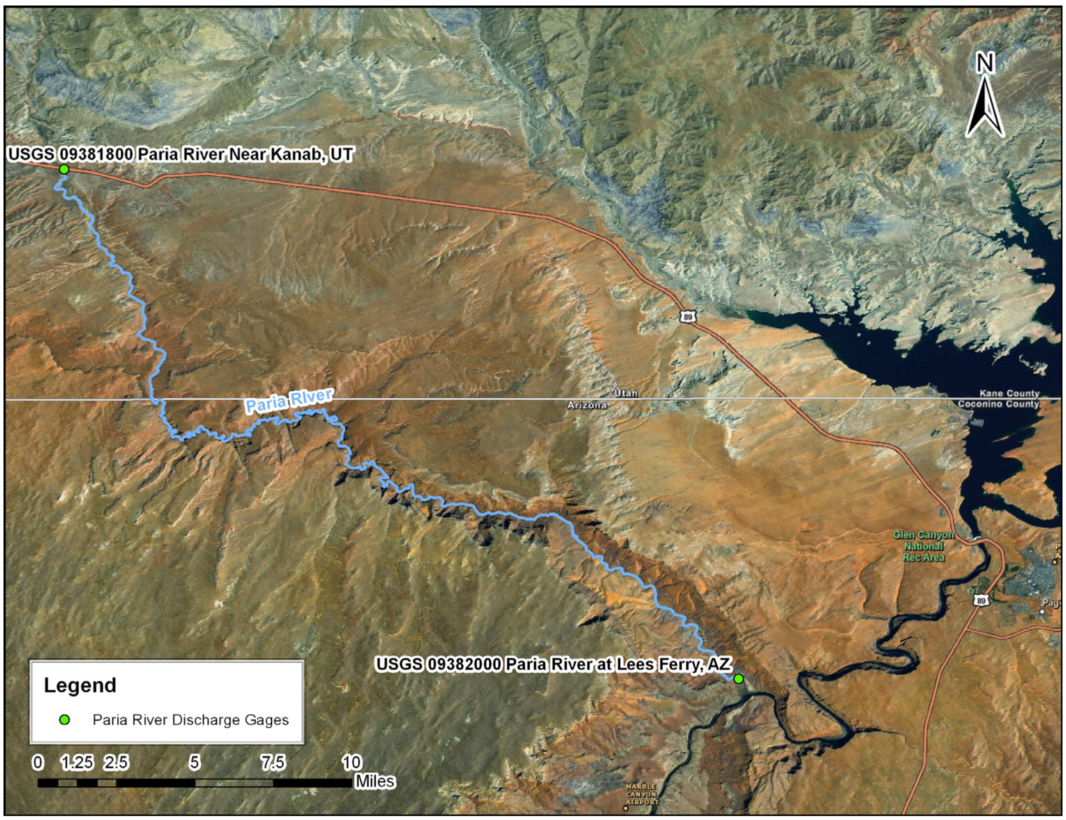

Figure 2. – Location Map of Paria River Discharge Gages

4. Additional Potential Data Sources

A recently installed National Oceanic and Atmospheric Administration (NOAA) National Climate Database Center (NCDC) weather station is located near Tropic, UT (above the Cannonville gage in upper basin). This weather station has a period of record from 7/14/2009 to present. Most floods events are likely caused by intense summer precipitation events in the uppermost 14% of the basin, near and upstream of the Cannonville, UT discharge gage (Topping, 1997, p. 60).

Also available for historical comparison is NCDC weather station located at Tropic, UT with a period of record from 7/1/1948 to 11/01/1999. These precipitation gage records could possibly be an additional data source for future analyses to predict the rainfall-runoff response in the Paria River Basin.

II. Methods

Data from the two lower discharge gages (near Kanab and at Lees Ferry) in the Paria River basin were compared to determine if a sequential flood event relationship could be statistically determined. Lacking real-time continuous sediment data, the discharge data will be used as a surrogate. The overlapping period of 15-minute interval data between these two discharge gages is from 9/17/2002 to 8/25/2010, which is almost 8 years. Several 'no data' time gaps were present in the two continuous discharge records. At the Kanab gage, approximately 101,982 15-minute time steps (~425 days) contain 'no data' values. At the Lees Ferry gage, approximately 19,642 15-minute time steps (~82 days) contain 'no data' values. Between the two discharge records, approximately 9,454 15-minute time steps (~39 days) contain 'no data' values for identical time steps. Time steps with 'no data' were given a value of 0.1 ft^3/sec to give the 'no data' time step a numerical value for future analyses.

With these two discharge records, the objective was to determine the probability of a desired minimum peak discharge of a resultant flood event occurring at the Lees Ferry gage, given a desired/set minimum indicator or "trigger" discharge value or minimum discharge ramp rate occurring upstream at the Kanab gage.

Discharge records were screened using various parameters in Microsoft Excel ® Visual Basic (VBA) code:

- Trigger discharge value is selected to screen out events below the minimum value
- Minimum resultant discharge value (i.e. the flood discharge are Lee's Ferry) is selected to screen out events below the minimum value
- A minimum 1-hour ramp rate can be set to screen out events below the minimum value
- A lag time and flood window time can be set to additionally filter events
- A flood seasonality filer (March-April or October-November) can be set to filter additional events.

The VBA code determines the number of resultant flood events above the desired minimum values, within the lag time, flood window range, and season. An additional “back window” filter was placed in the VBA code to make sure that observed indicator discharge values or discharge ramp rates that exceed the set minimum value for either indicator parameter are placed into singular indicator flood events, (i.e. make sure that there are no bi-peak flood hydrographs occurring within 4 hours of each other are considered as two separate flood events).

Figure 3 presents a conceptual diagram showing the key parameters used to determine the indicator and resultant flood events between the two Paria River discharge gages.

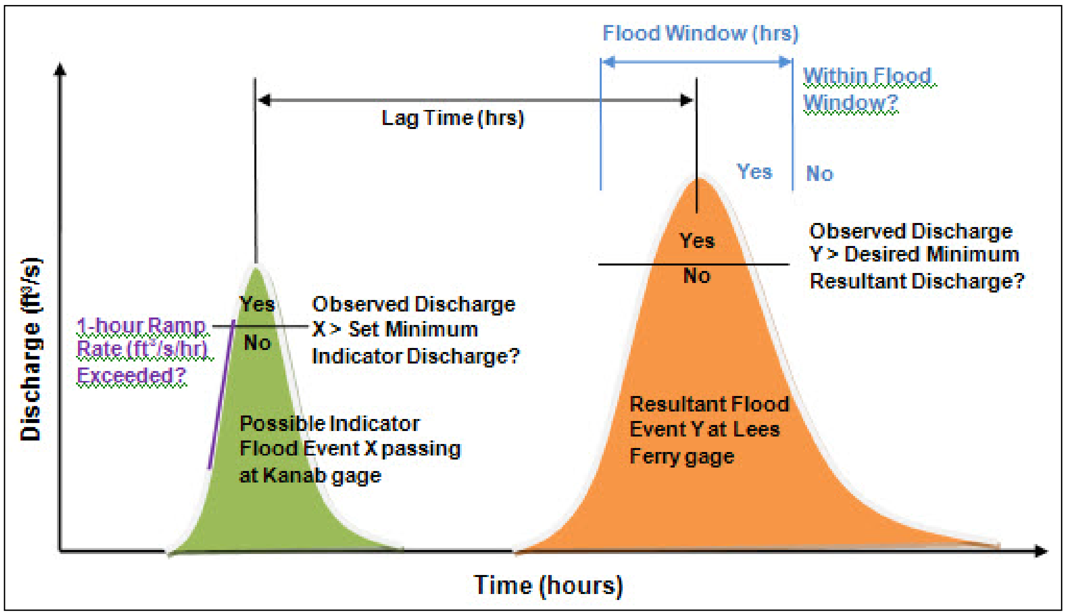

Figure 3. – Conceptual Diagram of Screening for Sequential Flood Events between Paria River Discharge Gages

A logistic regression model was fitted to the data in Matlab’s Statistics Toolbox given the indicator discharge or ramp rate values at the Kanab gage, number of resultant flood events above a set discharge or ramp rate, and the calculated proportion of indicator to resultant events. The logistic regression model was used to compute the probability of a resultant event given an indicator event and compute 95% confidence limits to show the uncertainty associated with the regression.

III. Results

A. Indicator Flood Events

1. Using Indicator Discharge

VBA code was used to determine the number of indicator or "trigger" flood events with a discharge equal to or above the set indicator discharge, and with a previous 1-hour discharge ramp rate above a set threshold in the period of record at the Kanab gage. To determine a range of values for this study, multiple incremental indicator discharge values ranging from 25 ft^3/s up to 3,200 ft^3/s, and varying indicator 1-hour discharge ramp rates from 0 to 500 ft^3/s per hour were used to determine the number of indicator events from the Kanab gage. In addition, varying the seasonality of the Kanab gage record was performed. In this study, the March-April and October-November bi-monthly periods, were screened out from the gage records. This incremental/variable method used to determine multiple sets of indicator flood events is presented as a test matrix in Table 2.

Table 2. – Test Matrix for Determining Indicator and Resultant Flood Events using Discharge and Ramp Rate in Combination

Minimum Indicator or Trigger Discharge (ft^3/s)	Previous Minimum 1-hour Discharge Ramp Rate (ft^3/s per hour)	Season
25	No Minimum Ramp Rate (0 ft^3/s per hour)	All Season
50	200 ft^3/s per hour	October-November
100	300 ft^3/s per hour	March-April
150	500 ft^3/s per hour	
200		
250		
300		
350		
400 up to 3,200 in 100 ft^3/s increments		

During the performance of the above test matrix in Table 2, as the indicator discharge increases, the number of indicator events in the period of record decreases and the number of indicator events determined between varied ramp rates becomes identical; therefore, indicator discharge without ramp rate was used for further analysis. Figure 4 presents the number of indicator events versus minimum indicator discharge for All Season. Figure 5 presents the number of indicator events versus minimum indicator discharge for the months of March-April. Figure 6 presents the number of indicator events versus minimum indicator discharge for the months of October-November.

Comparing between Figures 3 through 5, as expected, the most indicator flood events were from the All Season period. Fewer indicator flood events were determined during the March-April months compared to the October-November months.

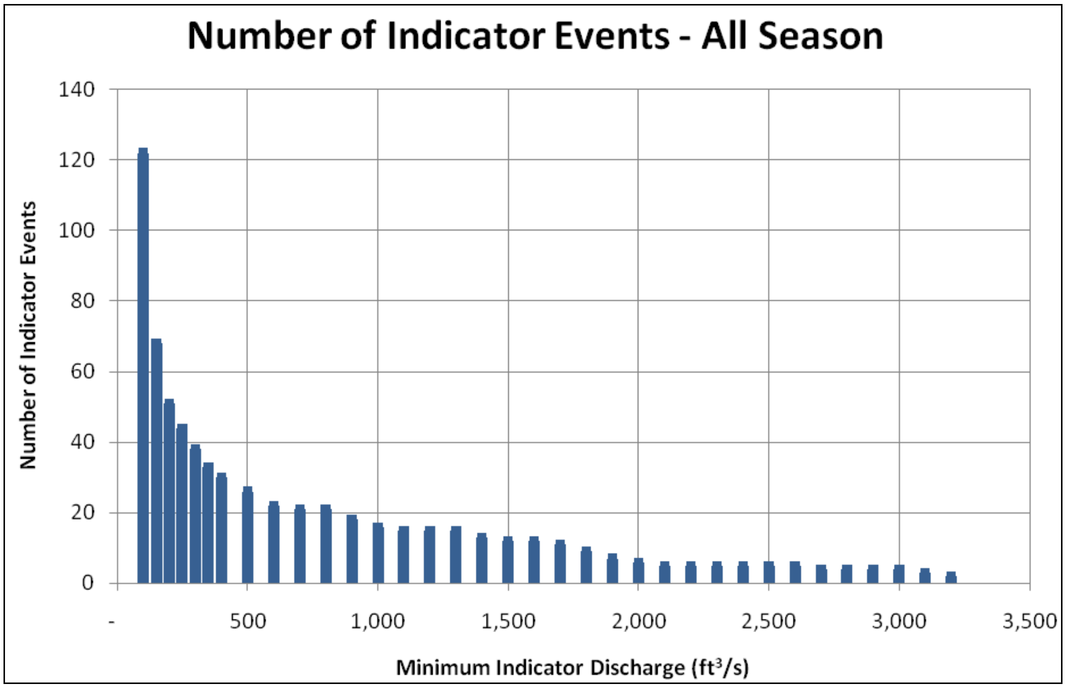

Figure 4. – Number of Indicator Flood Events at Kanab Gage, All Season, Indicator Discharge

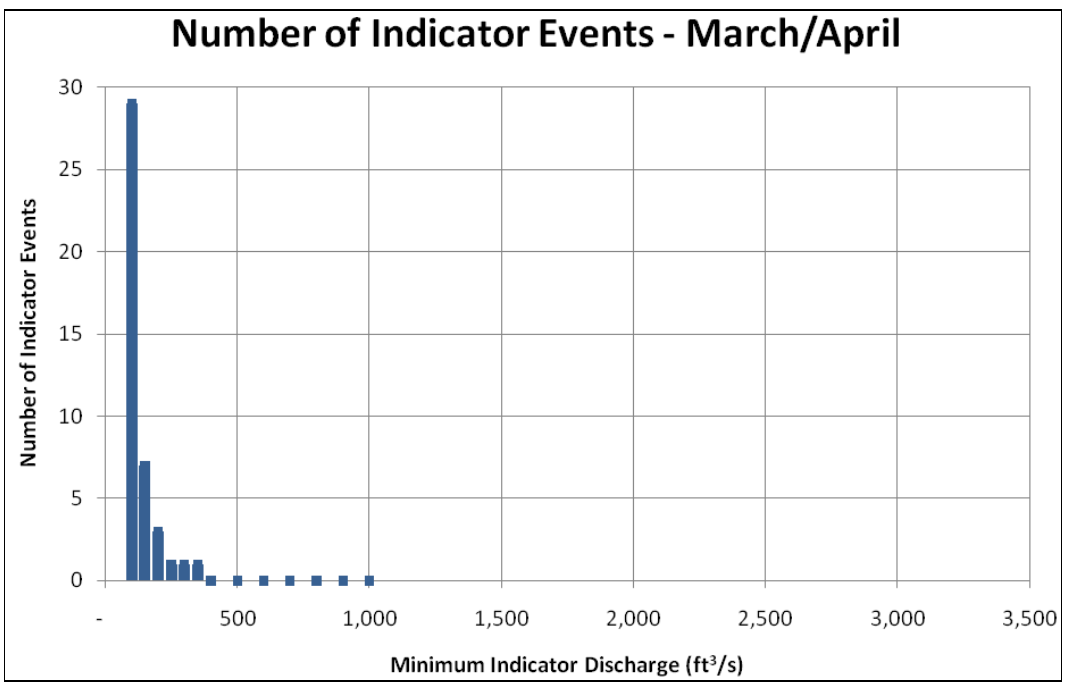

Figure 5. – Number of Indicator Flood Events at Kanab Gage, Months of March-April, Indicator Discharge

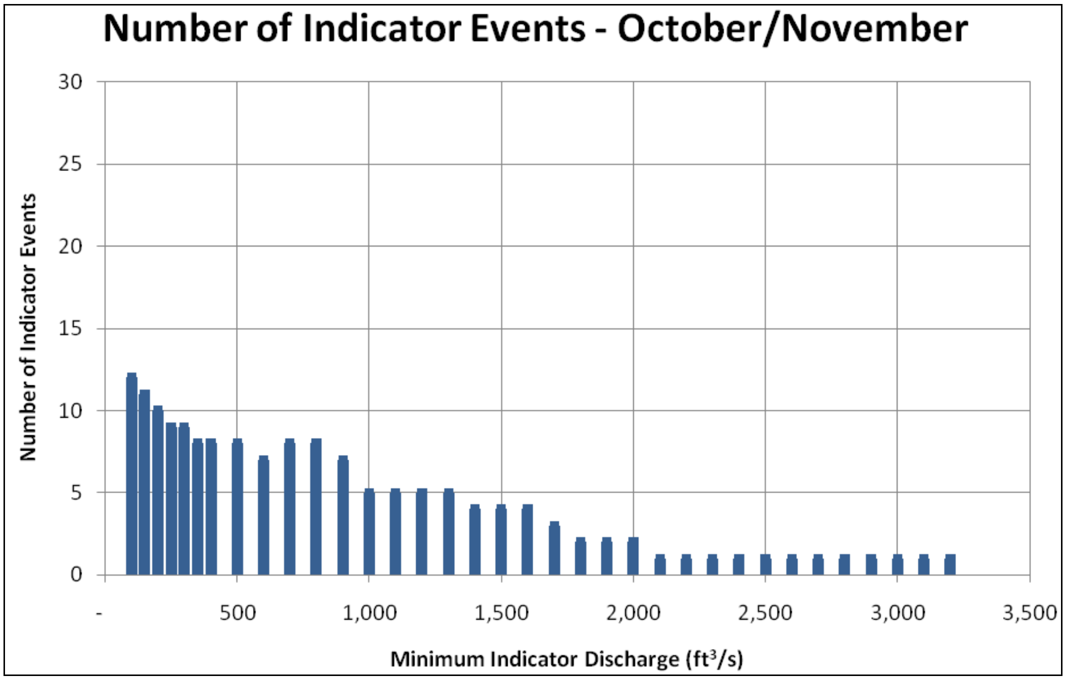

Figure 6. – Number of Indicator Flood Events at Kanab Gage, Months of October-November, Indicator Discharge

2. Indicator Flood Events Using Ramp Rate

VBA code was also used to determine the number of indicator or “trigger” flood events with a previous 1-hour discharge ramp rate above a set threshold in the period of record at the Kanab gage. To determine a range of values for this study, multiple incremental discharge ramp rate values ranging from 100 ft^3/s per hour up to 3,200 ft^3/s per hour were screened from the Kanab gage. In addition, varying the seasonality of the Kanab gage record was performed. In this study, the March-April and October-November bi-monthly periods, were screened out from the gage records. This incremental/variable method used to determine multiple sets of indicator flood events is presented as a test matrix in Table 3.

Table 3. – Test Matrix for Determining Indicator and Resultant Flood Events Using Ramp Rate Only

Previous Minimum 1-hour Discharge Ramp Rate (ft^3/s per hour)	Season
100 up to 3,200 in 100 ft^3/s increments	All Season
	October-November
	March-April

During the performance of the above test matrix in Table 3, as the indicator discharge ramp rate increases, the number of indicator events decreases.

Similar to the indicator flood results by season using discharge, there are more indicator flood events using indicator ramp rate during All Season (Figure 7) compared to the October-November months (Figure 8), which in turn have more than the March-April months (Figure 9).

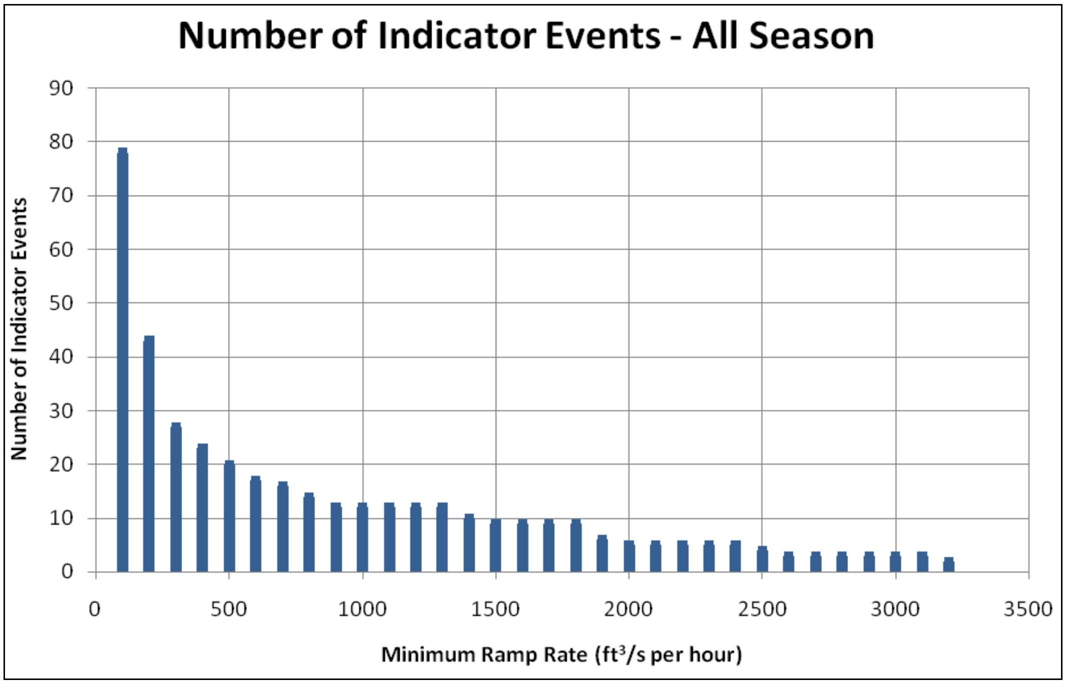

Figure 7. – Number of Indicator Flood Events at Kanab Gage, All Season, Indicator Ramp Rate

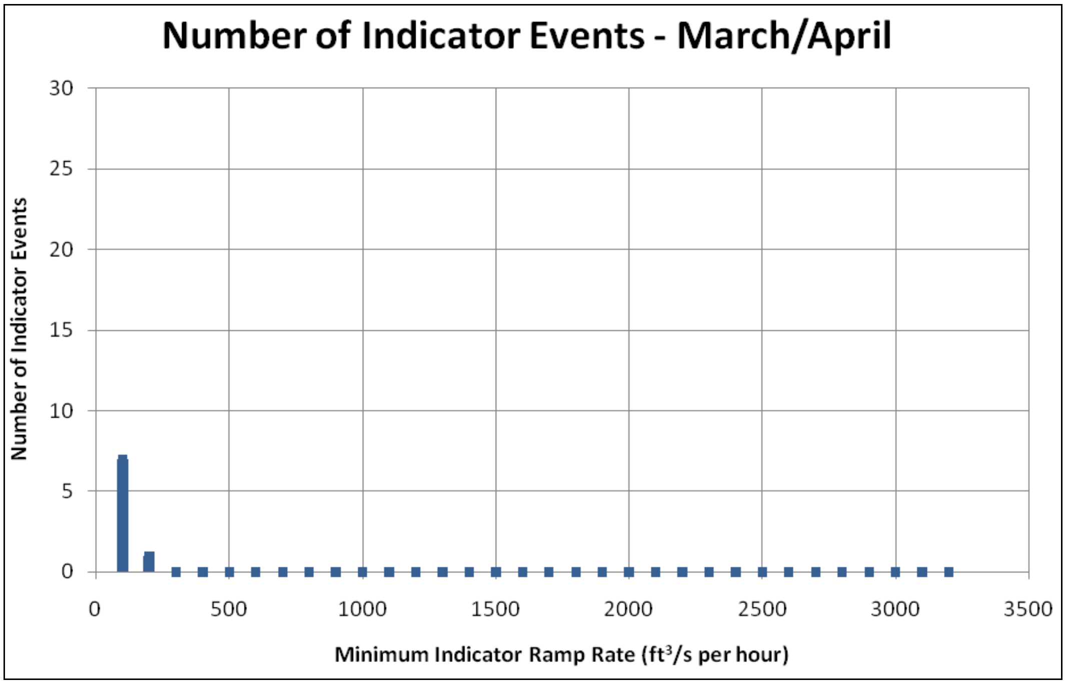

Figure 8. – Number of Indicator Flood Events at Kanab Gage, Months of March-April, Indicator Ramp Rate

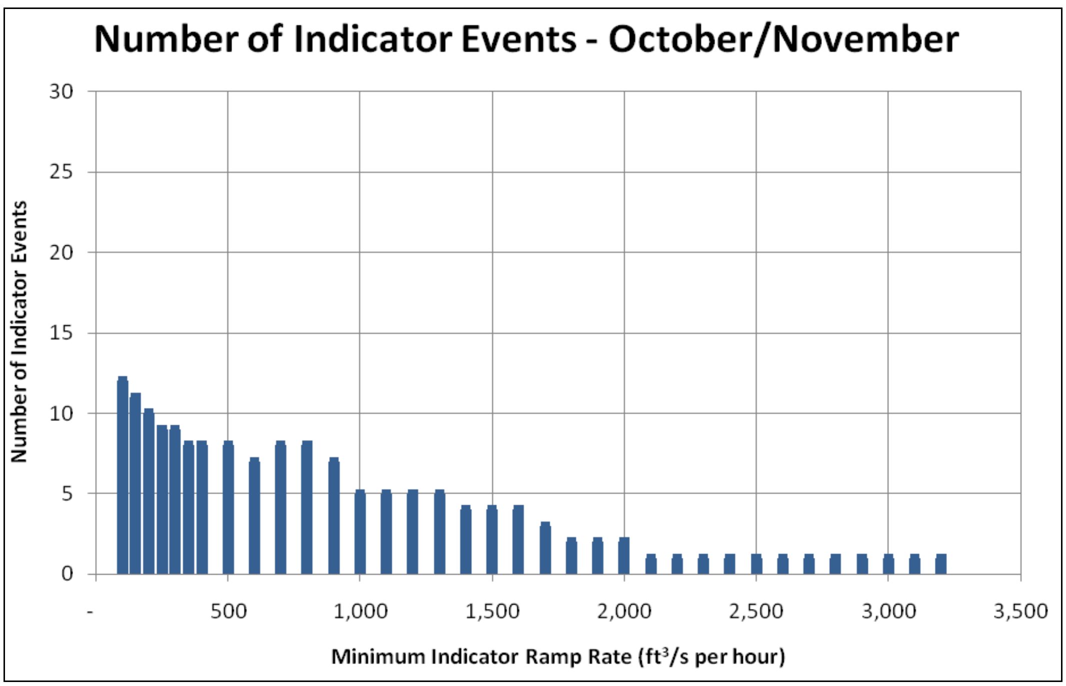

Figure 9. – Number of Indicator Flood Events at Kanab Gage, Months of October-November, Indicator Ramp Rate

3. *Flood Lag Time and Flood Window*

The distance between the Kanab and Lees Ferry discharge gages is approximately 40 miles; therefore the flow at Kanab will not be the same as the flow at Lees Ferry for a specific time and a lag time needs to be determined. The lag time can vary depending on the magnitude and volume of the flood event. To account for minor variances in the lag time of the resultant peak flood discharge, a flood window range parameter was added. This value was arbitrarily set as a two hour window, with one hour being before and one hour after the set lag time. To find the best fitting lag time in this study, several comparisons were made by holding the indicator discharge, indicator ramp rate, and desired resultant flood event discharge constant to determine the number of indicator and resultant flood events. Along with professional judgment, a single lag time with the most resultant events was selected based upon these results. Table 4 presents the results of the lag time comparison.

Table 4. – Comparison of Varying Lag Time between Indicator and Resultant Flood Events, All Season

Test Number	Minimum Indicator Discharge (ft^3/s)	Time Lag (hrs) w/ Flood Window within 2 hours of Lag Time	Minimum Resultant Flood Event Discharge (ft^3/s)	Number of Indicator Flood Events at Kanab (2002 - present)	Corresponding Number of Resultant Flood Events at Lees Ferry (2002-present)
1	1,000	4	500	16	8
2	1,000	5	500	16	8
3	1,000	6	500	16	10
4	1,000	7	500	16	14
5	1,000	8	500	16	14
6	1,000	9	500	16	14
7	1,000	10	500	16	11
8	1,000	11	500	16	11
9	1,000	12	500	16	9

Based on the results in Table 4 and by also performing a quick check of lower and higher resultant events during all of the different seasons, a lag time of 8 hours with a flood window range of 2 hours (giving a resultant flood event arrival range of 7 to 9 hours) was selected for the remainder of the study.

B. Statistical Analysis

The logistic regression model developed in Matlab was fitted to several different minimum resultant discharge values for each indicator parameter (discharge or ramp rate) and each season in order to show what key parameters can be used to reach a minimum 95% probability of a resultant discharge flood event occurring at the Lees Ferry gage. Based on the several sets of model fits, the threshold at which this probability will decrease with the current period of record was determined. Plotted results of the logistic regression models fitted to the data by minimum resultant discharge value are presented in this section by season.

1. All Season Results

Figure 10 presents the logistic regression model results with confidence limits for a resultant flood event of at least 500 ft^3/s at Lees Ferry, with an 8 hour lag time, using indicator discharge as the parameter at the Kanab gage.

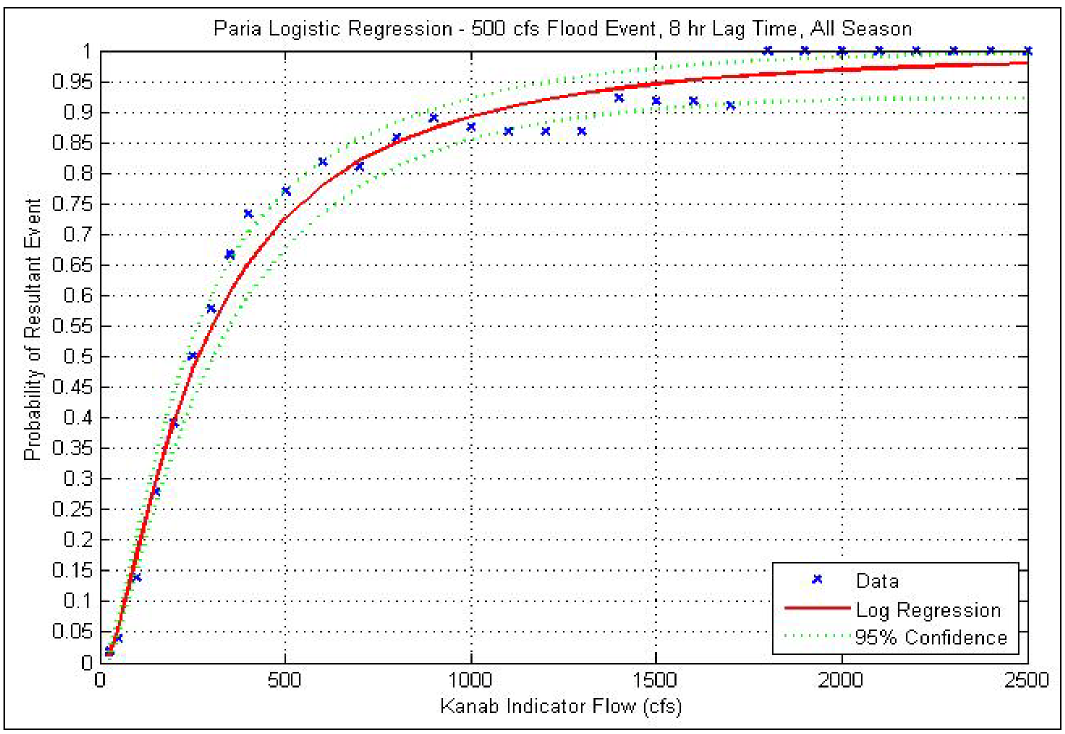

Figure 10. – Logistic Regression Results –500 ft^3/s Resultant Flood Event, All Season, Indicator Discharge

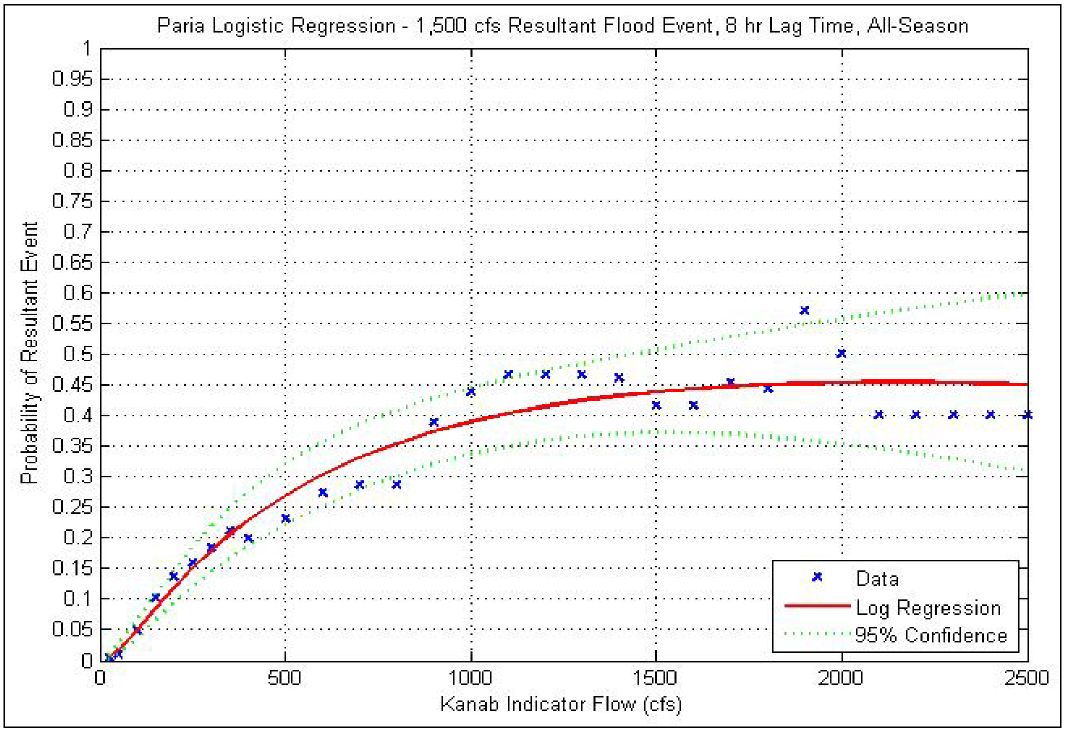

Figure 11. – Logistic Regression Results –1,500 ft^3/s Resultant Flood Event, All Season, Indicator Discharge

The regression results in Figure 10 show that using a discharge 1,500 ft^3/s at the Kanab gage as the indicator flood event gives a 95% probability of 500 ft^3/s resultant flood event occurring 7 to 9 hours later at the Lees Ferry gage.

Figure 11 presents the logistic regression model results with confidence limits for a resultant flood event of at least 1,500 ft^3/s at Lees Ferry, with an 8 hour lag time, using indicator discharge as the parameter at the Kanab gage.
The regression results in Figure 11 show that at best there is a 45% probability of a resultant flood event with a discharge of at least 1,500 ft^3/s occurring 7 to 9 hours later at Lees Ferry during all seasons for an indicator flood of 2,000 ft^3/sec at the Kanab gage.

Next, the 1-hour discharge ramp rate is used as the indicator parameter to determine the probability a resultant flood. Figure 12 presents the 500 ft^3/s resultant event logistic regression results for all seasons using an 8 hour lag time and ramp rate as the indicator parameter. Figure 13 presents the 1,500 ft^3/s minimum resultant event logistic regression results for all seasons using an 8 hour lag time and ramp rate as the indicator parameter.

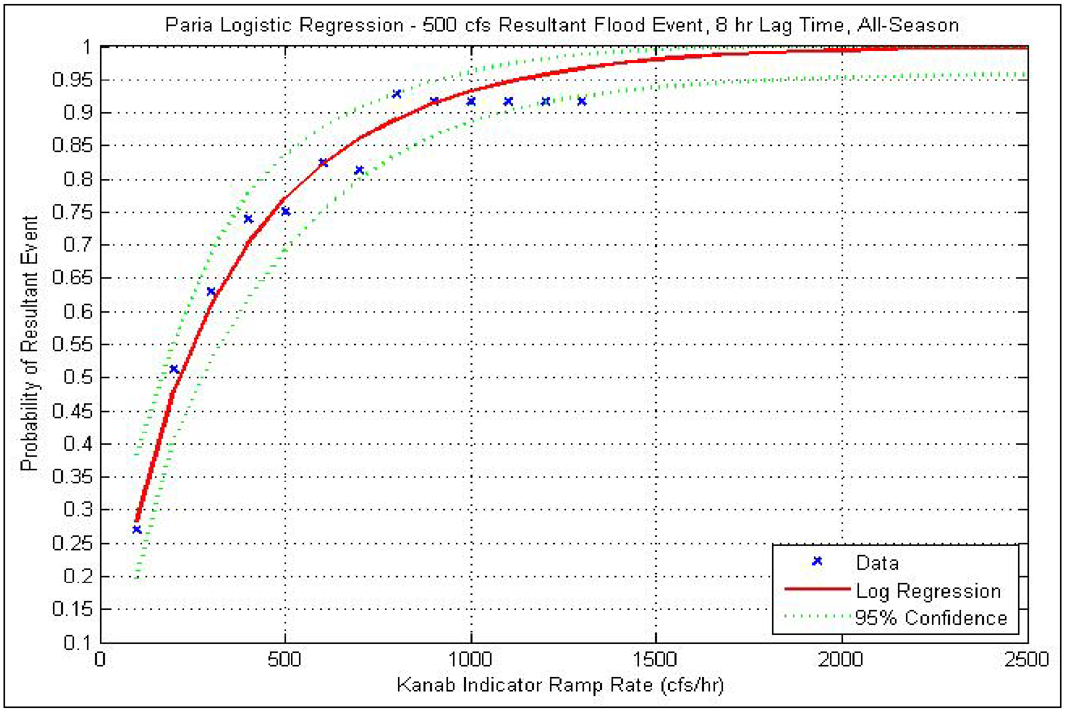

Figure 12. – Logistic Regression Results – 500 ft^3/s Resultant Flood Event, All Season, Ramp Rate

The regression results in Figure 12 show that using a ramp rate of 1,200 ft^3/s per hour at the Kanab gage as the indicator flood event gives a 95% probability of 500 ft^3/s resultant flood event occurring 7 to 9 hours later at the Lees Ferry gage.

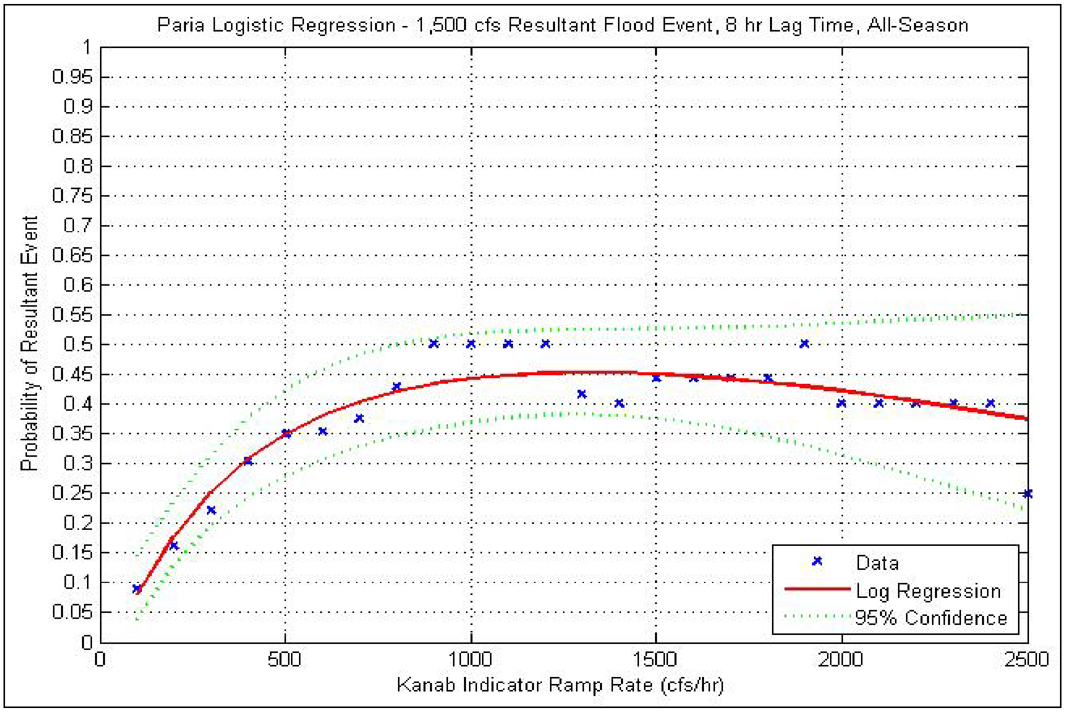

Figure 13. – Logistic Regression Results – 1,500 ft^3/s Resultant Flood Event, All Season, Ramp Rate

The regression results in Figure 13 show that at best there is a 45% probability of a 1,500 ft^3/s resultant flood event occurring 7 to 9 hours later at the Lees Ferry gage during all seasons using a ramp rate of 1,300 ft^3/s per hour at the Kanab gage.

2. March-April Results

Figure 14 presents the logistic regression model results with confidence limits for a minimum resultant flood event of at least 100 ft^3/s at the Lees Ferry gage during the months of March-April, with an 8 hour lag time, using discharge as the indicating parameter.

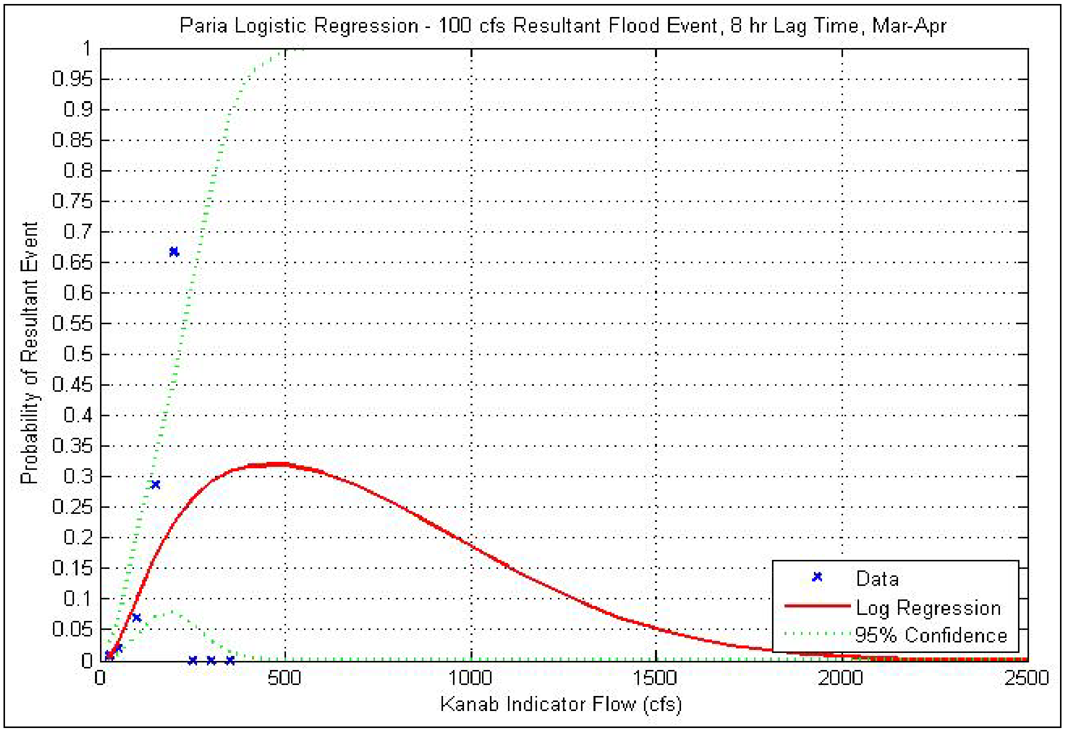

Figure 14 – Logistic Regression Results –100 ft^3/s Minimum Resultant Flood Event, March-April Months, Indicator Discharge

Results in Figure 14 show a poor regression model fit to the observed minimum indicator and minimum resultant events for a minimum resultant flood event of 100 ft^3/s during the March-April months. During this bi-monthly period, there are 29 indicator events in the record. There were poor regression model fits observed for larger resultant flood events as well.

A poor regression model fit is also observed when using ramp rate as the indication parameter.

3. October-November Results

Figure 15 presents the logistic regression model results with probability and confidence limits for a resultant flood event of at least 500 ft^3/s occurring at the Lees Ferry gage during the months of October-November, with an 8 hour lag time, using discharge as the indicating parameter.

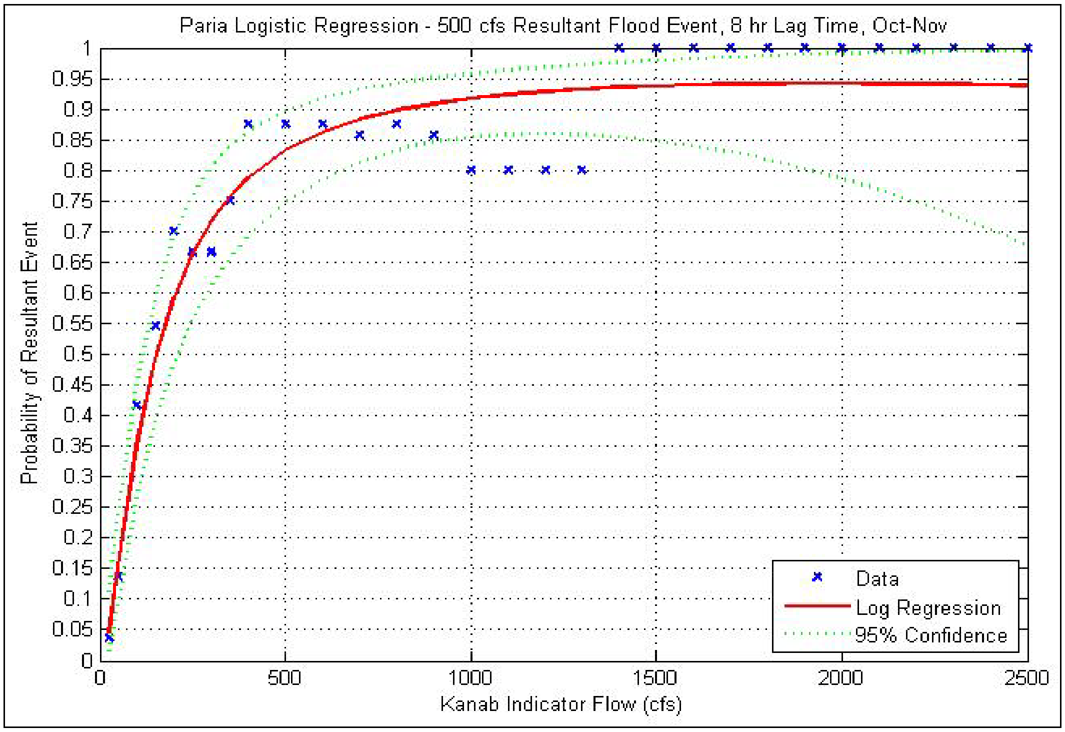

Figure 15. – Logistic Regression Results – 500 ft^3/s Minimum Resultant Flood Event, October-November Months, Indicator Discharge

The regression results in Figure 15 show that at an indicator flood event with a discharge of at least approximately 1,900 ft^3/s at the Kanab gage, there is a 95% probability that a flood event of at least 500 ft^3/s will occur 7 to 9 hours later at the Lees Ferry gage during the months of October-November. Also observed in the regression results in Figure 15 is that the 95% confidence bounds widen as the minimum indicator flow increases. This is due to the overall decrease in the observed number of indicator and resultant flood events in the record as the minimum indicator discharge value increases.

Figure 16 presents the logistic regression model results with probability and confidence limits for a resultant flood event of at least 1,500 ft^3/s occurring at the Lees Ferry gage during the months of October-November, with an 8 hour lag time, using discharge as the indicating parameter.

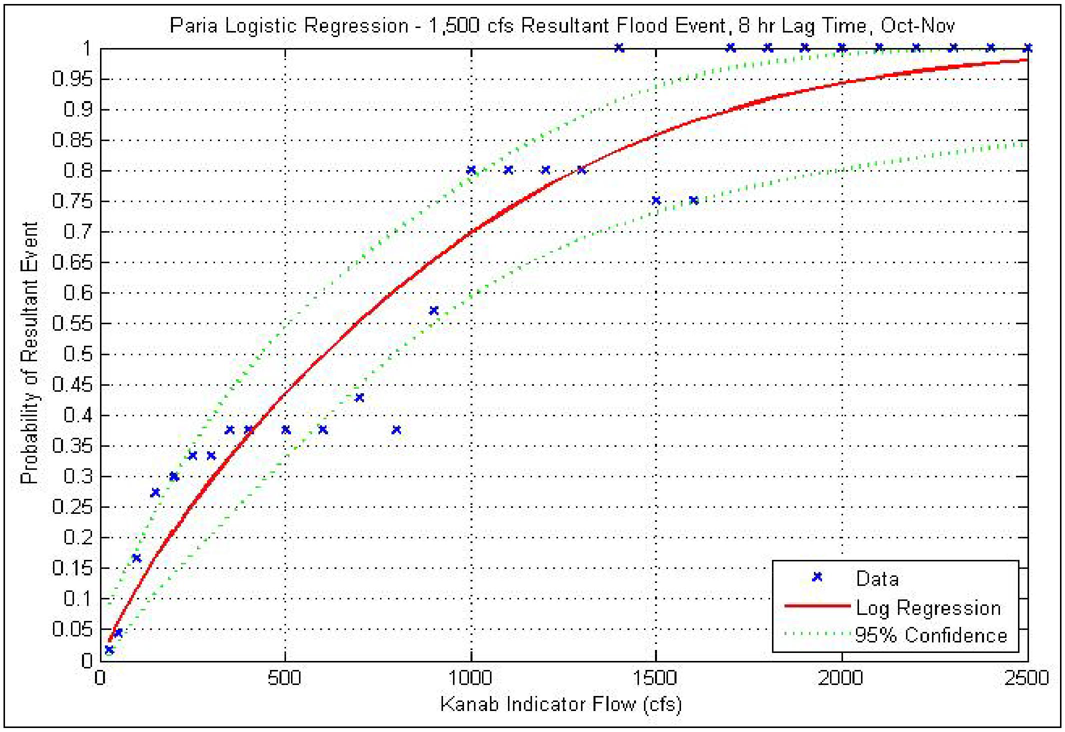

Figure 16. – Logistic Regression Results – 1,500 ft^3/s Minimum Resultant Flood Event, October-November Months, Indicator Discharge

The regression results in Figure 16 show that at an indicator flood event with a discharge of at least approximately 2,000 ft^3/s at the Kanab gage, there is a 95% probability that a flood event of at least 1,500 ft^3/s will occur 7 to 9 hours later at the Lees Ferry gage during the months of October-November. Also observed in the regression results in Figure 16 is that the 95% confidence bounds widen as the minimum indicator flow increases. This is due to the overall decrease in the observed number of indicator and resultant flood events in the record as the minimum indicator discharge value increases. It is important to note that for indicator flood events with a minimum discharge greater than 2,000 ft^3/s, there is only one corresponding indicator and resultant flood event that has occurred in the period of record. Therefore, this 95% probability is based on one event on record.

Figure 17 presents the logistic regression model results with probability and confidence limits for a resultant flood event of at least 500 ft^3/s occurring at the Lees Ferry gage during the months of October-November, with an 8 hour lag time, using discharge ramp rate as the indicating parameter.

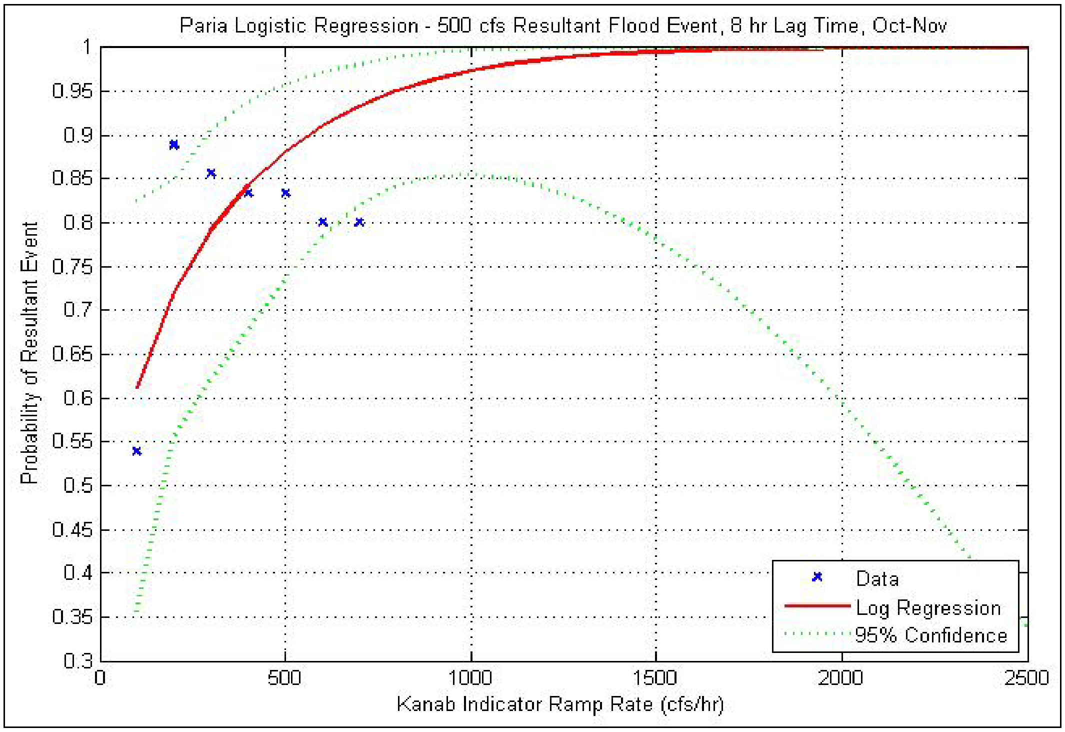

Figure 17. – Logistic Regression Results – 500 ft^3/s Minimum Resultant Flood Event, October-November Months, Ramp Rate

The regression results in Figure 17 show that at an indicator flood event with a ramp rate of at least approximately 800 ft^3/s per hour at the Kanab gage, there is a 95% probability that a flood event of at least 500 ft^3/s will occur 7 to 9 hours later at the Lees Ferry gage during the months of October-November.

Figure 18 presents the logistic regression model results with probability and confidence limits for a resultant flood event of at least 1,500 ft^3/s occurring at the Lees Ferry gage during the months of October-November, with an 8 hour lag time, using discharge ramp rate as the indicating parameter.

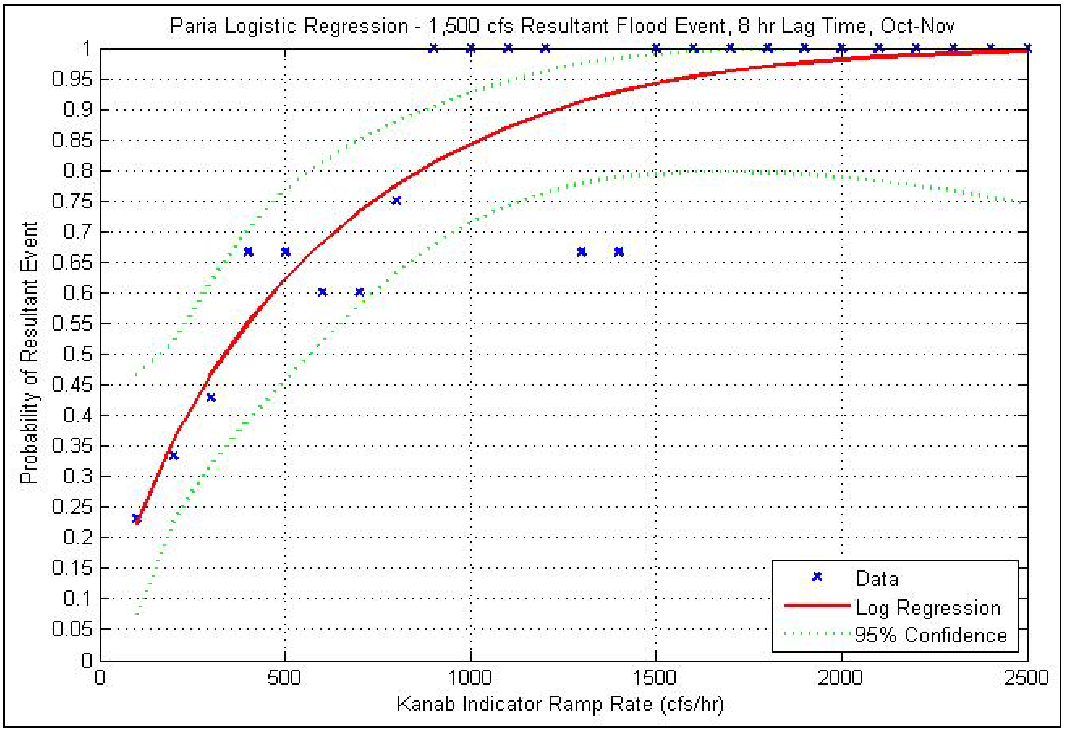

Figure 18. – Logistic Regression Results – 1500 ft^3/s Minimum Resultant Flood Event, October-November Months, Ramp Rate

The regression results in Figure 18 show that at an indicator flood event with a ramp rate of at least approximately 1,500 ft^3/s per hour at the Kanab gage, there is a 95% probability that a flood event of at least 1,500 ft^3/s will occur 7 to 9 hours later at the Lees Ferry gage during the months of October-November. Also observed in the regression results in Figure 18 is that the 95% confidence bounds widen as the minimum indicator flow increases. This is due to the overall decrease in the observed number of indicator and resultant flood events in the record as the minimum indicator discharge value increases. It is important to note that for indicator flood events with a minimum discharge greater than 2,000 ft^3/s, there is only one corresponding indicator and resultant flood event that has occurred in the period of record. Therefore, this 95% probability is based on one event on record.

IV. Conclusions

The results in this analysis are based on the stream gage records for the Kanab and Lees Ferry gages from 9/17/2002 to 8/25/2010. A series of commands and tools are applied to the gage records to determine a probability-based relationship for use as a decision-making tool.

During the analysis, an optimal lag time of 7 to 9 hours between the Kanab and Lees Ferry gages was determined to provide the best results between indicator and resultant events when varying the lag time.
Table 4 summarizes the logistic regression analysis. Between the two indicators analyzed (discharge and ramp rate) for all seasons, for a 7 to 9 hour lag time, assuming a 95% probability as the threshold probability, and for a minimum resultant flood event of 500 ft3/s at the Lees Ferry gage, the indicator ramp rate gives a lower indicator value (1,200 ft3/s per hour) at the Kanab gage compared to using indicator discharge (1,500 ft3/s) as the indicator value.

For the months of March-April, there a poor relationship between indicator and resultant flood events between the Kanab and Lees Ferry gages, primarily because there are no significant (>100 ft3/s) floods that occur during this period.

Based on the results in Figure 18, during the months of October-November, a minimum resultant discharge of 1,500 ft3/s at the Lees Ferry gage can be predicted at a 95% probability for an indicator ramp rate of 1,500 ft3/s per hour at the Kanab gage. It is important to note, however, that there is only one event in the record for both gages, where the both the indicator and resultant events is satisfied for discharges greater than 2,000 ft3/s during the months of October-November.

In addition, only one event greater than bankfull discharge (3,180 ft3/s) has occurred in the 9 year instantaneous record for both gages. The flood duration of bankfull or larger flood events are also short (mean 3.66 hours, Topping, 1997 p.53), increasing the difficulty in indicating a statistically-triggered flood event at the Kanab gage.

Although statistical relationships were found between the two gages, the lack of multiple high flow events creates uncertainty when using these relationships for operations decisions. As the period of record between the two gages increases, the uncertainty associated with the logistic regression equations will decrease and a more reliable prediction of flood events higher than 1,500 ft3/s at the Lees Ferry gage will be possible.

If the option of coordinating HFE with flood flows from Paria is pursued further, several additional investigations should be conducted to investigate the sediment delivery and storage processes at the confluence of the Paria and Colorado Rivers.

Table 5. – Summary of Logistic Regression Analysis

Resultant Discharge at Lees Ferry Gage (ft^3/sec)	Indicator Discharge at Kanab Gage (ft^3/sec)			Indicator Ramp Rate at Kanab Gage (ft^3/sec per hour)		
	All Season	March-April	October-November	All Season	March-April	October-November
500	1,500	N/A	1,900	1,200	N/A	800
1,500	2,000 (45%)	N/A	2,000	1,300 (45%)	N/A	1,500

A 95% probability threshold was used except where noted in parentheses.

Literature Cited

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. Volumes 1 and 2. *Dissertation.* University of Washington Department of Geological Sciences. 405 pp.