APPENDIX H:

CULTURAL RESOURCES TECHNICAL INFORMATION AND ANALYSIS

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The assessment of potential impacts on cultural resources relied on three factors identified during the Long-Term Experimental and Management Plan (LTEMP) assessment process as the primary factors affecting the stability of historic resources in the canyons: (1) erosion (Thompson and Potochnik 2000; Damp et al. 2007; Spurr and Collette 2007), (2) inundation (Baker 2013), and (3) visitor effects (Bulletts et al. 2008, 2012; Jackson-Kelly et al. 2013). Metrics were formulated for these factors to quantitatively analyze the effects on cultural resources of the LTEMP alternatives based on modeling of discharge and sediment loads. The metrics are:

- Wind Transport of Sediment Index
- Flow Effects on Cultural Resources in Glen Canyon Index
- Time Off River Index

This appendix discusses the modeling of each metric and presents a detailed discussion of the modeling results. The metrics were developed through consultation with subject matter experts, findings in published papers and reports, and consideration of comments from cooperating agencies. See Section 3.8 for a more detailed description of Grand Canyon cultural resources and Chapter 2 for a detailed description of the LTEMP alternatives.

H.1 WIND TRANSPORT OF SEDIMENT

Prior to the construction of Glen Canyon Dam, periodic large-magnitude storm events would flood the Colorado River and deposit fluvial sediment onto high-elevation terraces. Wind also transported sediment from the active river channel onto the high-elevation terraces and helped to maintain the sediment deposits (Draut 2012). The deposited sediment buried and protected evidence of past human activity within the floodplain of the river. However, the dam's closure in 1963 trapped most of the sand that would have been transported into the Glen Canyon and Grand Canyon reaches of the Colorado River, and operations reduced the magnitudes of annual peak flows and increased the magnitudes and durations of low flows (baseflows). The decrease in magnitude of sediment-rich peak flows has lowered the elevation of the area scoured by high flows and at which new sand can be deposited. The increase in elevation and duration of low flows has promoted the expansion of riparian vegetation onto bare sand (Sankey et al. 2015) and has limited the duration of time sand is dry and subaerially exposed, both of which reduce the wind's ability to transport sediment (East et al. 2016; Draut 2012; Draut and Rubin 2008). These changes decreased the renewal of sediment to high-elevation terraces downstream of the dam (East et al. 2016). With limited rejuvenation of sand, landscapes and archaeological sites are more prone to erosion, which can expose sites found along the riparian zone of the river (East et al. 2016; Collins et al. 2016; Sankey and Draut 2014).

Sediment deposited along the riverbank above the elevation of normal operational flows and below the elevation of peak operational flows can be transported by the wind and deposited onto high-elevation terraces, many of which contain archaeological sites (East et al. 2016). This windblown sediment can make the landscape less vulnerable to erosion from rainfall-runoff processes and can potentially increase the preservation potential of archaeological sites on these high-elevation terraces (East et al. 2016). It has been observed that the optimal annual timeframe for this transfer of sediment is in the spring months, when a reduced amount of rainfall and strong winds create conditions for windblown sediment transport (Draut and Rubin 2008). A wind transport metric was developed based on principles identified by Draut and Rubin (2008) to address the possibility of systemwide benefits to archaeological sites located on these higher terraces.

H.1.1 Wind Transport of Sediment—Methods

The Wind Transport of Sediment Index (WTSI) evaluates the availability of fine sediment for wind transport to cover cultural resources at higher elevations (i.e., those properties located at stages above 31,500 cfs). Optimal conditions for wind transport of sediment occur when (1) fine sediment is deposited by flows above the stage of normal operations and (2) low flows occur during the windy season, which exposes more sand for redistribution by the wind. These two conditions are accounted for by the Wind Transport of Sediment Index (WTSI) using the following equation (Eq. H.1), where SLI is the Sand Load Index and FF is the flow factor*:*

$$WTSI = SLI \times Average(FF)_{2014-2033} \tag{H.1}$$

Both of the inputs for the metric (SLI and FF) are indices ranging from 0 to 1. The resulting Wind Transport of Sediment Index is a value from 0 to 1, where a value of 1 corresponds to the most potential movement of sediment by the wind, and therefore has the highest likelihood to contribute to the preservation of cultural resources. Both elements of the equation (SLI and FF) are limiting factors in the sense that the highest value between the two is the highest possible output. This mirrors the occurring environmental limitations—no more sediment can be transported than available, while, regardless of availability, wet sand is not likely to be easily transported by the wind.

The WTSI is calculated for a total of 63 scenarios representing different hydrologic (20 traces) and sediment conditions (3 traces), and weighted by the historical exceedance percentage of the sediment traces included in the scenario. Because of modeling limitations, environmental factors—such as sandbar erosion due to fluctuations in water level, rainstorm events that may further saturate soil, and vegetation barriers that could prevent sediment transport by the wind—were not incorporated into the metric. Complex parameters like these would require more assumptions, which could result in less confidence in the model.

The SLI is an index of the potential sand deposited on sandbars along the river channel in Marble and Grand Canyons above normal stage elevations (31,500 cfs). The SLI is calculated as the ratio of the cumulative sand load at flows greater than 31,500 cfs relative to the total cumulative sand load at all flows. The sand load, or the mass of sand in transport by the river, is calculated at RM 30 and is computed by a version of the Sand Budget Model (Wright et al. 2010) for the 20-year LTEMP modeling period. A larger SLI (on a scale of 0 to 1) indicates a greater potential for sediment deposition. The SLI is described in more detail in Appendix E. The SLI was calculated using Equation H.2:

$$SLI = \frac{\sum_{2014-2033} \textit{Sand Load at dam discharges} > 31{,}500\ cfs}{\sum_{2014-2033} \textit{Sand Load at all dam discharges}} \qquad \text{(H.2)}$$

The FF represents the relative exposure of dry, fluvial sand along the banks of the river available for wind transport. An increase or decrease in dam discharge will increase or decrease the downstream river elevation, respectively. Therefore, a lower discharge will expose a greater amount of sediment. For this metric, maximum daily flows above normal river stage (8,000 cfs) are considered increasingly worse for sediment exposure. The maximum daily discharge (Q_{max}) modeled by GTMax-Lite represents the maximum discharge released from Glen Canyon Dam in cubic feet per second (cfs) and thus the extent of dry sand for each day. The yearly FF is the average of FF_{Daily} (Eq. H.3) for the spring months of March through June.

$$FF_{Daily} = \left\{\begin{matrix} \text{if } Q_{max} \le 8{,}000; & 1 \\ \text{if } 8{,}000 < Q_{max} < 31{,}500; & 1.34 - 0.0000425 \times Q_{max} \\ \text{if } Q_{max} \ge 31{,}500; & 0 \end{matrix}\right\} \qquad \text{(H.3)}$$

Note that although the FF only takes into account the months of March through June, the SLI incorporates the entire year. This is because the exposure of sand is most prominent during the windy season, but the sediment transported during those months is continuously built up throughout the year.

H.1.2 Wind Transport of Sediment—Results

WTSI values calculated for the LTEMP alternatives under historical flow and sediment inputs are shown in Figure H-1. The metric values represent the *potential* for sand to be transported to cultural sites rather than the actual transport that would occur or the level of protection that transport may provide to cultural sites. This results in some uncertainty with regard to actual differences in impact among the alternatives based on this metric. Our conclusions on relative impact are based on comparisons of the metric values calculated for Alternatives B, C, D, E, F, and G, and their long-term strategies against Alternative A (the no-action alternative), which has the same basic operational discharge pattern as current operations under Modified Low Fluctuation Flows (MLFF). Research done to date on the effects of windblown sand and archaeological sites has examined operations since the closure of Glen Canyon Dam including MLFF conditions. This research has shown that the number of archaeological sites ideally situated to receive aeolian sand supply from the river has decreased since the completion of the dam and most recently under MLFF conditions (East et al. 2016). When sites are no longer ideally situated to receive sand supply, they are at elevated risk from erosion (East et al. 2016). These changes in sand supply and erosion risk can be attributed to several specific characteristics and effects of MLFF, including the absence of sediment-rich

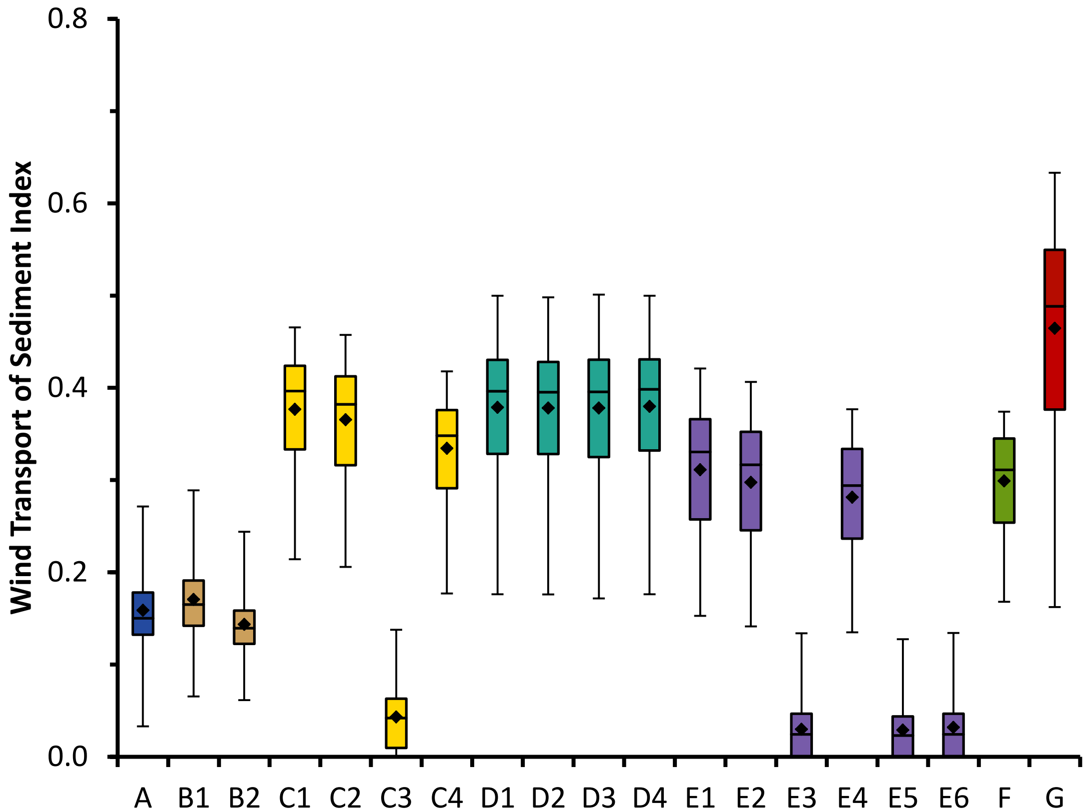

FIGURE H-1 Wind Transport of Sediment Index Values for the LTEMP Alternatives (letters) and Associated Long-Term Strategies (numbers) (Index values of 1 are considered optimal. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

floods above 45,000 cfs, increases in riparian vegetation, and decreases in open, dry sand area that is available for aeolian transport within the active river channel (East et al. 2016).

Of the long-term strategies analyzed, one for each alternative was selected as most representative of the alternative as fully implemented. These representative long-term strategies were B1, C1, D4, and E1, and Alternatives A, F, and G. All of the representative long-term strategies B1, C1, D4, and E1, as well as Alternatives F and G, scored greater than Alternative A because they have more frequent high-flow experiments (HFEs). Long-term strategies B2, C3, E3, E5, and E6 rank below Alternative A. With the exception of long-term strategy B2, HFEs are not conducted for these strategies, and flows above 31,500 cfs would occur rarely, if at all. Recall that one of the primary assumptions for this metric is that flows above 31,500 cfs are the primary mechanism for sediment deposition at higher elevations. If there are no high flows to deposit sand at higher elevations along the banks of the river, there is no new sediment to be moved by the wind. Increased flow fluctuations in long-term strategy B2 cause it to rank below Alternative A.

Alternative G scores the highest of all the alternatives, with an average WTSI nearly three times greater than Alternative A. With the highest number of HFEs and the lowest maximum daily flows during the windy months (Figure H-2), this alternative has parameters ideal for wind-transport of fluvial sediment to high-elevation terraces that contain cultural resources. The second highest scoring long-term strategy, D4, is not significantly different from long-term strategies D1, D2, D3, and C1 (statistical differences between means based on a three-factor analysis of variance [ANOVA] followed by Tukey's Studentized Range Test).

On the whole, the WTSI is highly correlated with the number of HFEs and the corresponding SLI. The relationship between SLI and HFEs is discussed in Appendix E. The similarity between WTSI and HFEs can be seen by comparing Figure H-1 with the average number of HFEs in Figure H-2. The WTSI is highly correlated with the SLI because the average maximum discharge between March and June for each of the alternatives is within 5,000 cfs (standard deviation of 0.05). With minimal difference in flow, the amount of sediment for distribution becomes the determining factor for the index. The exception to this is Alternative F. Figure H-3 shows a sample trace of the typical 8.23 million acre-feet (maf) release year. In April, May, and June, the discharge of Alternative F is higher than that of all other alternatives. Although Alternative F was determined to have the second highest potential sand deposition (highest SLI), it ultimately has an average WTSI value lower than Alternatives C, D, E, and G, as larger discharges of water create less ideal conditions for wind transport.

Long-term strategies C2 and E2 feature low summer flows and trout management flows (TMFs) when conditions trigger them. Reallocation of water volume from low summer flows can cause increased discharge in other portions of the water year. This reallocation combined with

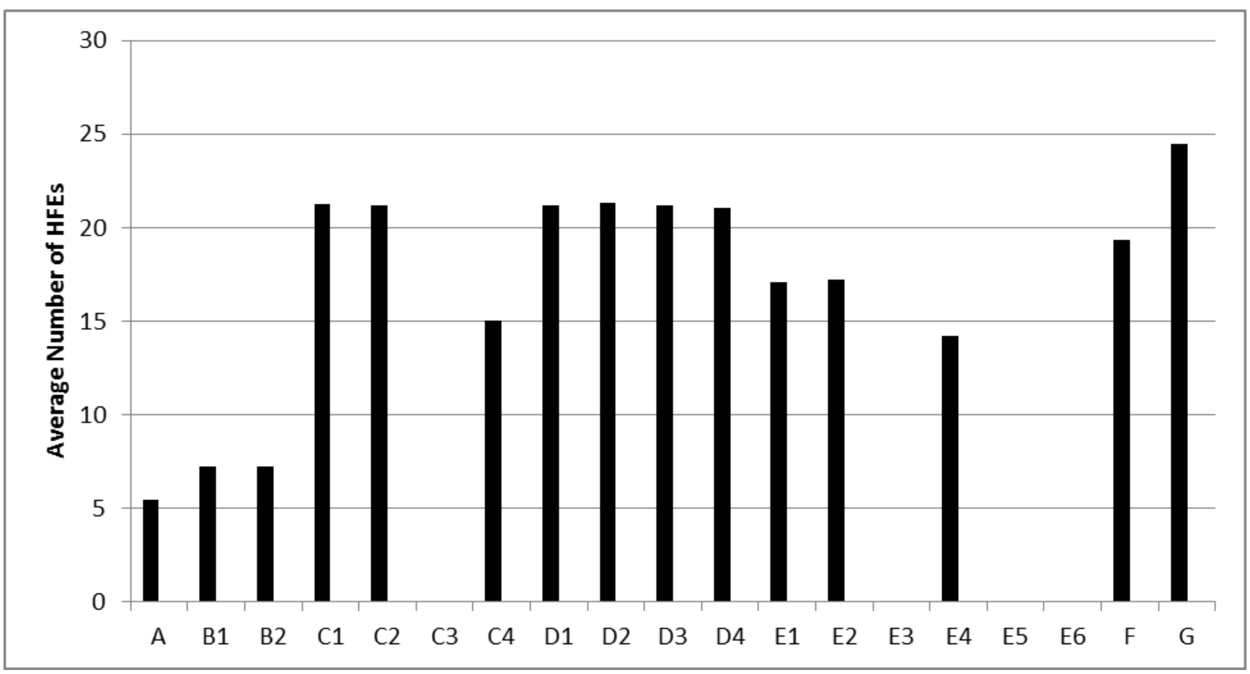

FIGURE H-2 Average Number of HFEs in the 20-Year LTEMP Period

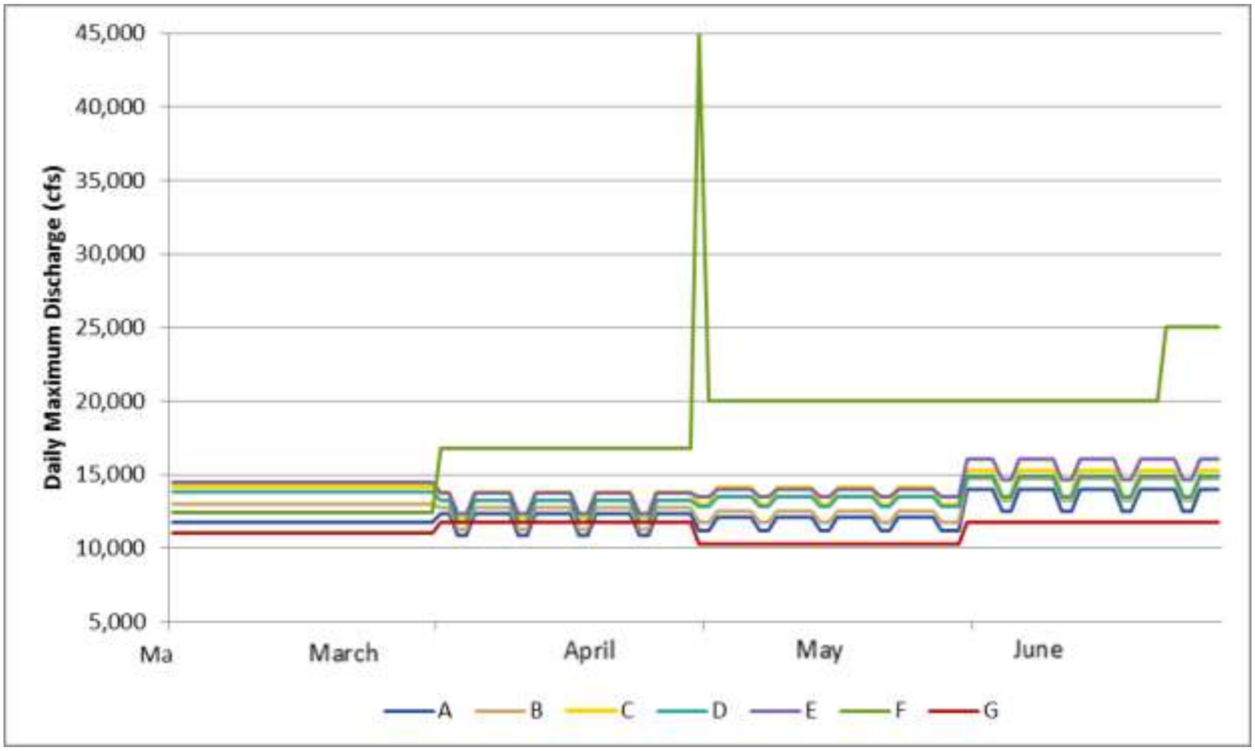

FIGURE H-3 Daily Maximum Discharge in a Typical 8.23-maf Water Volume Release Year from the Glen Canyon Dam during the Windy Season of March–June

the high-flow portion of TMFs causes long-term strategies C2 and E2 to rank lower than their base alternatives. Similarly, the exclusion of spring HFEs in long-term strategies C4 and E4 decrease their WTSI in comparison to long-term strategies C1 and E1.

The WTSI is useful for understanding the interplay between the components of the alternatives. Alternatives that incorporate strategies for enhancing sediment retention (i.e., Alternatives C, D, E, and G, which have reduced fluctuations or more even monthly volumes) have higher WTSI values. The metric also illustrates through Alternative F the effect that flow operations can have on wind transport. Index values are lower for Alternative F because the alternative features higher flows in the windier periods of the spring and summer, which negates some of the benefits of the higher sediment retention indicated in the SLI. Although the metric is beneficial for comparative and theoretical purposes, it reflects idealized conditions for wind transport of sediment that cannot be easily translated into actual site preservation. The extent to which wind transport of sediment can mitigate the erosion occurring in cultural sites on high-elevation terraces remains unknown.

H.2 FLOW EFFECTS ON CULTURAL RESOURCES IN GLEN CANYON

The construction of Glen Canyon Dam significantly scoured the immediate downstream Glen Canyon reach of the Colorado River and cut off nearly all of the sediment supply from upstream. Unlike further downstream sections of the river, a lack of significant tributaries in Glen Canyon results in very little sediment deposition on river banks of the canyon. In fact, high flows meant to distribute sediment have been shown to degrade terraces in the Glen Canyon reach (Grams et al. 2007). Archaeological sites located in Glen Canyon are also not associated with significant wind deposition of sediment (Anderson 2006). Without the rejuvenation of sediment, higher flows can increase erosion within the Glen Canyon, which is a concern for significant archeological sites.

Anderson (2006) identified 14 archaeological sites within Glen Canyon that were being affected by river-based arroyos or gullies. However, only one of these sites, commonly referred to as Ninemile Terrace, was determined to have erosional features that are unequivocally related to direct impacts of river operations. Bank stability at Ninemile Terrace, and at other terraces with the potential to contain cultural resources, is partially dependent on the accumulation of material at the base of the slope. Removal of this protective material through erosion leaves the lower-bank material prone to a continuing cycle of undercutting, collapse, and removal. This, in turn, contributes to slumping of the upper-bank material, whether dry or saturated. The flow at which the base of the slope begins to erode serves as the “flow elevation threshold.” Flows at or above this threshold have the potential to adversely affect cultural resources through bank erosion and destabilization (Baker 2013). Time-lapse photography from the November 2012 HFE shows that the inundation of the existing base of the slope at Ninemile Terrace occurs at a flow of 23,200 cfs.

Ninemile Terrace reflects many characteristics of other sites in Glen Canyon and was considered representative of other Glen Canyon terrace sites for determining the effects of water flow on high-elevation terraces. In the absence of direct field measurements to further clarify a flow elevation threshold, the flow rate of 23,200 cfs was identified by Glen Canyon National Recreation Area staff as an approximate measure to represent the flow elevation above which erosional processes could contribute to impacts that have the potential to adversely affect cultural resources.

H.2.1 Flow Effects on Cultural Resources in Glen Canyon—Methods

Impacts on cultural resources in the Glen Canyon reach were determined by calculating the number of days per year that the maximum daily flow would be >23,200 cfs. A higher number represents the increased potential for erosion of terraces that contain cultural resources. The maximum daily flow is used to capture all instances where flow is high enough to contribute to erosional processes. As with the WTSI, a total of 63 scenarios of different hydrologic and sediment conditions were analyzed.

This metric determines the relative difference among alternatives for the potential impacts of flow on cultural resources. Research would be needed to determine the number of days of high flow that would produce noticeable or extensive impacts on cultural sites.

H.2.2 Flow Effects on Cultural Resources in Glen Canyon—Results

Figure H-4 shows the number of days per year during which flows would be >23,200 cfs for each alternative. The average number of days flows would be >23,200 cfs ranges from 18 to 36 among the alternatives. High maximum values of 50–77 days would occur under all alternatives (as noted by the upper whisker) and would occur in years with high water volumes released from Glen Canyon Dam (e.g., annual average release volume for the trace was 11.5 maf or higher).

Alternative A has the highest number of days per year during which flows would be >23,200 cfs. Alternative A most closely represents the current conditions of MLFF. Long-term strategies C3, E3, E5, and E6 (long-term strategies with no HFEs) have average values that are lower than under Alternative A, but they differ from that number by no more than 3 days. Alternative F would have the highest number of days per year during which flows would be >23,200 cfs; it averages 14 days per year more than under Alternative A. Alternative F, therefore, has the highest potential for impacts on terraces that contain cultural resources in

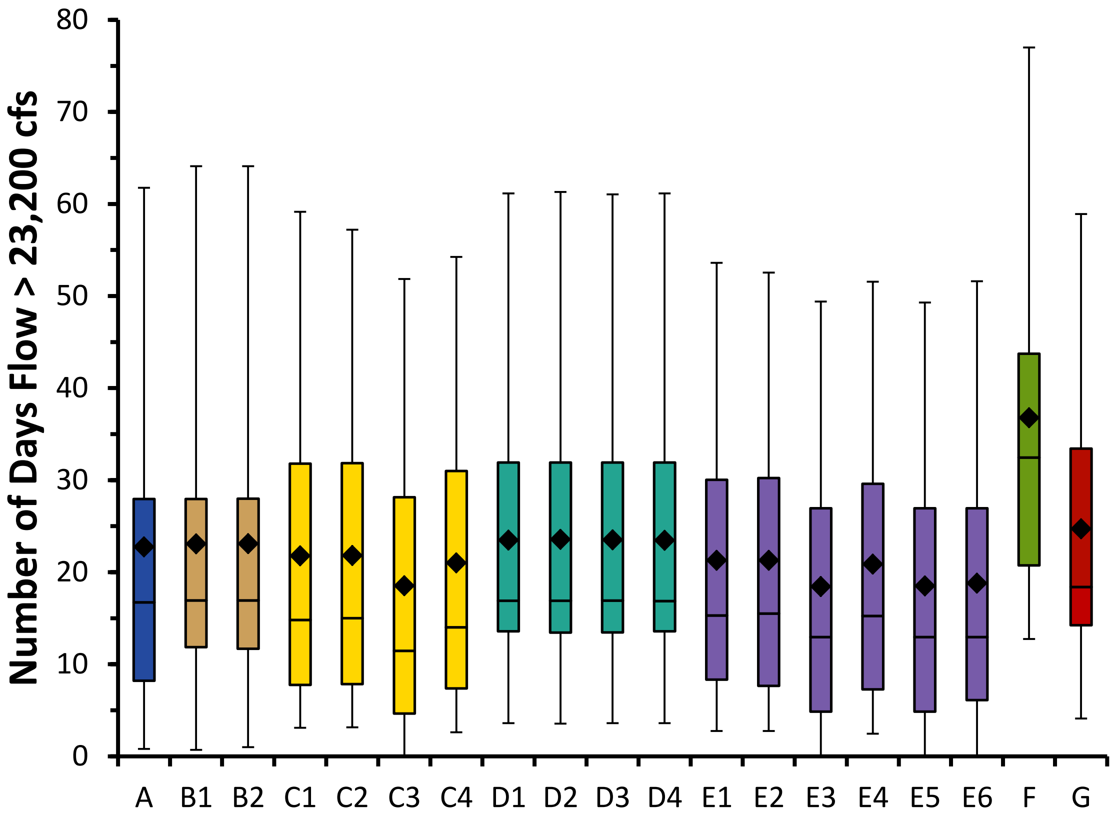

FIGURE H-4 Number of Days per Year Flows Would Be >23,200 cfs under LTEMP Alternatives (Letters) and Long-Term Strategies (Numbers) (Flows of this magnitude have the potential to affect cultural resources in Glen Canyon. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

Glen Canyon. The higher number of high-flow days under Alternative F results from the relatively high spring flows between May and June (see Section 2.2.6). For the remaining alternatives, average number of days per year during which flows would be >23,200 cfs are within 4 days of those under Alternative A.

Besides the high spring flows of Alternative F and HFEs under all alternatives, operational changes within long-term strategies seem to have minimal effect on the number of days per year during which flows would be >23,200 cfs. Long-term strategy B2 includes tests of hydropower improvement flows (i.e., operations with wider water release fluctuations in high electrical demand months than the base operations of long-term strategy B1). Although hydropower improvement flows increase within-day flow fluctuations, in most cases, the altered maximum flow does not exceed 22,000 cfs. Therefore, long-term strategies B1 and B2 have nearly identical values and are not significantly different. Long-term strategies C2, D3, E2, and E5 all have low summer flows. Low summer flows result in higher flows at other times of year, but do not affect the number of days per year during which flows would be >23,200 cfs, and these long-term strategies will not have any effect on this metric. TMFs would also have minimal effect on this metric.

Although the number of HFEs (Figure H-2) in the alternatives differ, these differences have little effect on the number of days per year during which flows would be >23,200 cfs. This occurs because HFEs are relatively short (Figure H-5), and the large volume released under the HFE must be compensated for by releasing less water at other times of the year (Figure H-6). Because all alternatives must release the same annual volume of water, alternatives with HFEs may have lower releases at other times of years than those without. The effect on the metric

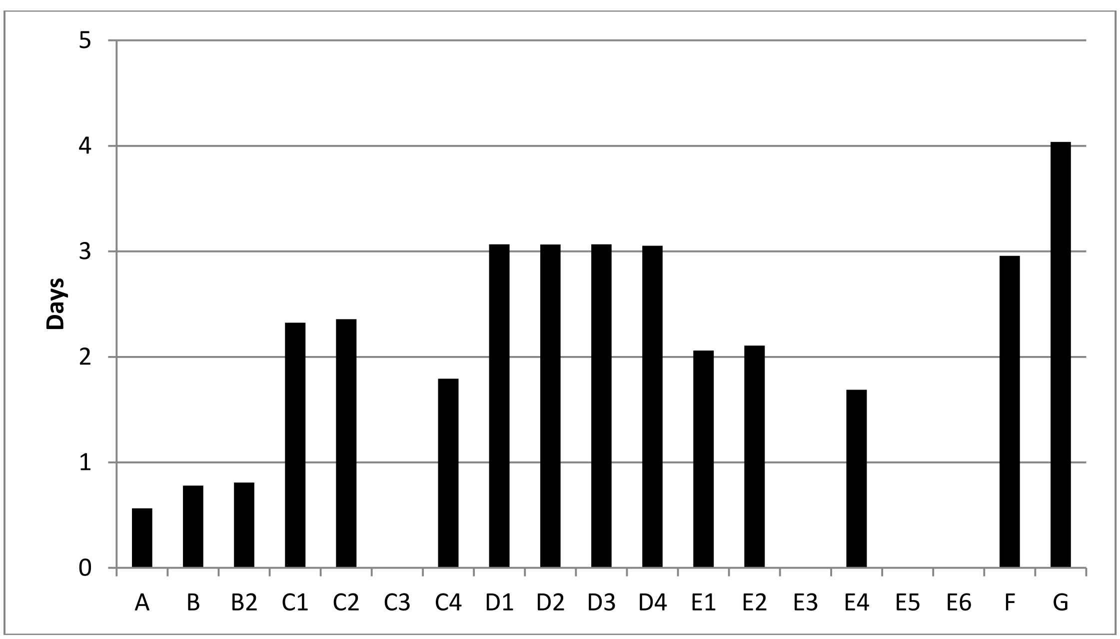

FIGURE H-5 Average Number of Days of an HFE Event per Year

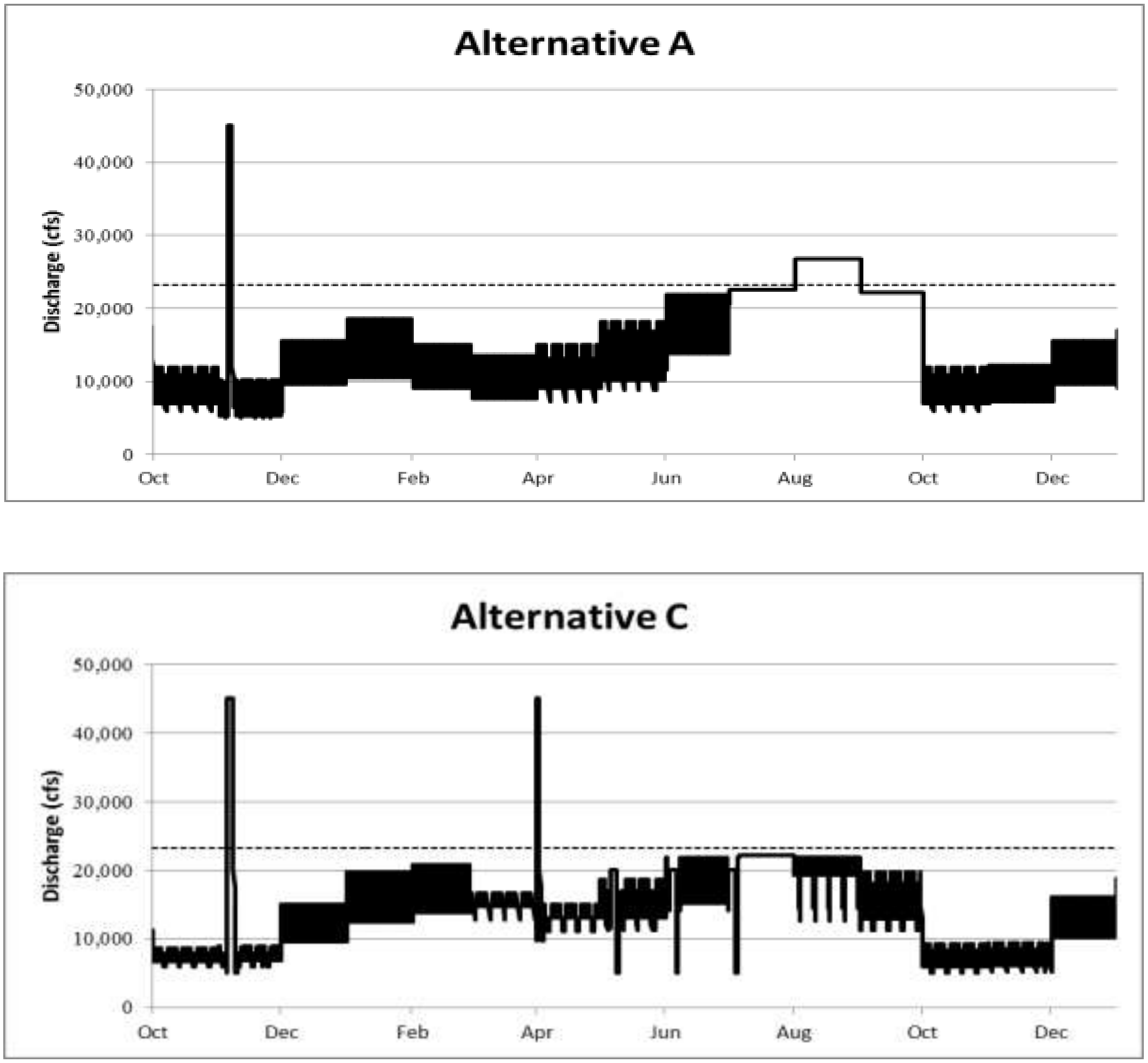

FIGURE H-6 Modeled Glen Canyon Dam Discharge for the Same Year (the line represents 23,200 cfs)

would be greater in years of high volume (≥10 maf) when equalization flows would be implemented according to the Interim Guidelines (Reclamation 2007).

This explains why Alternatives A and B, with minimal HFE events, have nearly the same metric value as alternatives like Alternative C with more than four times the number of HFEs (Figure H-2). Although Alternative C has two HFEs (Figure H-6) and Alternative A has only one, Alternative A must release more water in August to compensate. Historically, precipitation was higher than conditions in recent years; therefore, equalization flows may be triggered less frequently and days above 23,200 cfs might be less than for those based on historical flows. The 50th and 25th percentile values are more applicable to recent climate conditions seen in the Glen Canyon region. In addition, the variability (noted by the length of box) in the value is a result of the variability in the release volume between water years, HFEs, and the interaction between the two for a particular alternative.

H.3 TIME OFF RIVER

Greater discretionary time for whitewater rafters to explore the canyons downstream of Glen Canyon Dam increases the likelihood that they could have an impact on archaeological sites by creating trails to sites or looting or vandalizing sites. When the river is moving at a faster pace and boat travelers arrive at their destination earlier, their discretionary time off river increases. It is therefore hypothesized that higher flows may increase the potential for adverse human contact with archeological sites.

H.3.1 Time Off River—Methods

The Time Off River Index (TORI) represents the degree to which flows could affect visitor potential to interact and disturb cultural sites. Grand Canyon visitor numbers vary depending on the time of the year. Recreational activity is more common in the warmer summer months, less so in the spring and fall months, and even less in the colder winter months. The yearly TORI (Eq. H.4) is the ratio of the sum of seasonal ratios that designate flows ideal for minimal visitor-site interaction. Summer has the highest weight (0.54), while winter has the lowest (0.15) and spring and fall are in between (0.31). The TORI is a 0–1 value, where 1 equals the least discretionary time for visitors to access archaeological sites, and, therefore, the lowest potential for impacts on cultural sites.

$$TORI = \left[0.15\left(\frac{\sum_{winter} ORFF}{\sum Days_{winter}}\right) + 0.31\left(\frac{\sum_{\frac{spring}{fall}} ORFF}{\sum Days_{\frac{spring}{fall}}}\right) + 0.54\left(\frac{\sum_{summer} ORFF}{\sum Days_{summer}}\right)\right] \qquad \text{(H.4)}$$

An overall annual mean TORI value for the 20-year modeling period was developed for each alternative and used as the performance metric (Eq. H.5).

$$TORI = Average\ (TOR_{annual})_{2014-2033} \qquad \text{(H.5)}$$

The Off River Flow Factor (ORFF) represents the potential for discretionary time off river. The discharge level at which boats begin to exceed typical river travel times is 10,000 cfs. However, once flows reach more than 31,500 cfs, visitors are more likely to stay at campsite areas rather than travel in a turbulent river. Daily average flows (Q_{avg}) represent the average release from Glen Canyon dam in cubic feet per second. Average daily discharge from the dam was modeled in GTMax-Lite. The ORFF is a 0–1 value, where 1 indicates the lowest potential for discretionary time off river and therefore the lowest potential for increased visitation of archaeological sites. Specifically, the average daily ORFF is assigned as follows (Eq. H.6), where the value within the brackets in the right column is assigned to $ORFF_{Daily}$ if the equation in the left column is satisfied:

$$ORFF_{Daily} = \begin{cases} \text{if } Q_{avg} \leq 10{,}000; & 1 \\ \text{if } 10{,}000 < Q_{avg} < 31{,}500; & 1.465 - 0.0000465 \times Q_{avg} \\ \text{if } Q_{avg} \geq 31{,}500; & 0 \end{cases} \quad \text{(H.6)}$$

As with the WTSI, a total of 63 scenarios of different hydrologic and sediment conditions were analyzed.

H.3.2 Time Off River—Results

TORI does not specify how much additional discretionary time off river a visitor may experience. Instead, TORI is intended to determine the potential for visitors to spend more time off of the river exploring—which could result in more cultural resources being visited and possibly affected—by examining the flows under the various alternatives as compared to Alternative A.

A summary of TORI results is provided in Figure H-7. Except Alternative F, all of the alternatives and their long-term strategies performed relatively similarly for this metric. Values

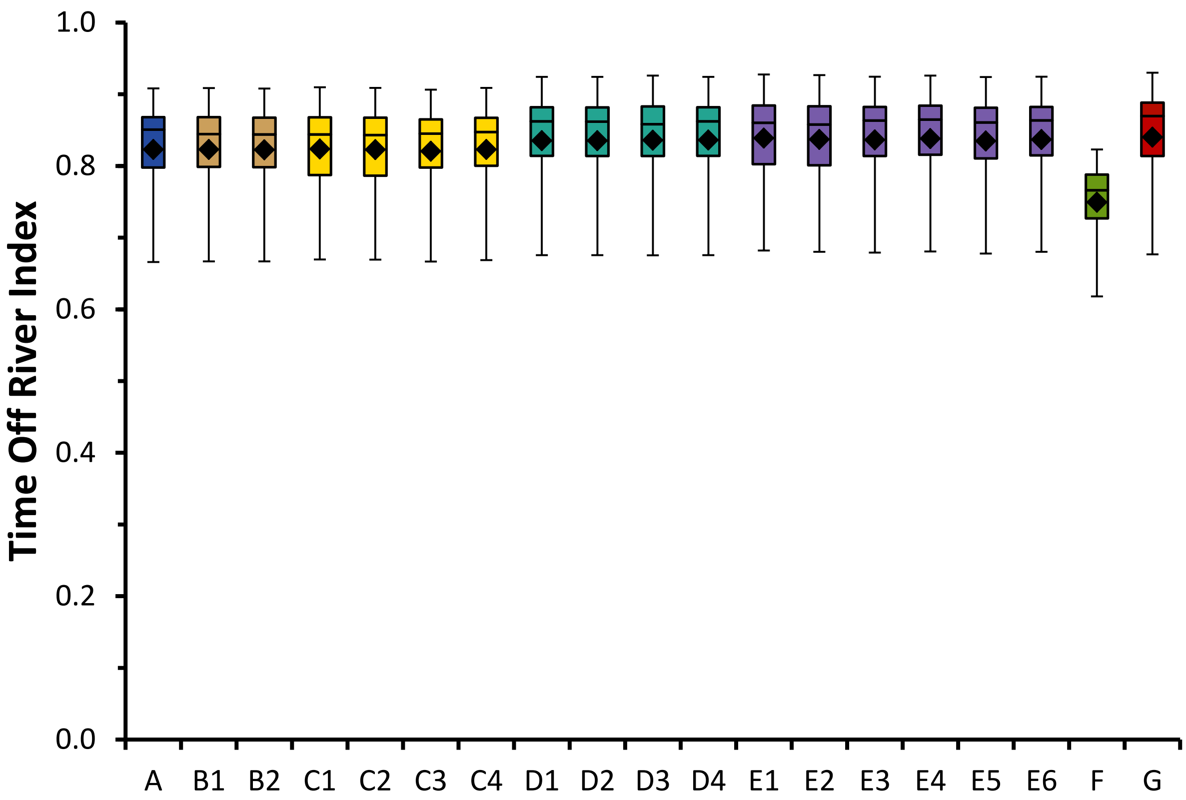

FIGURE H-7 Time Off River Index Values for All LTEMP Alternatives (Letters) and Associated Long-Term Strategies (Numbers) (Index values of 1 are considered optimal. Note that diamond = mean; horizontal line = median; lower extent of box = 25th percentile; upper extent of box = 75th percentile; lower whisker = minimum; upper whisker = maximum.)

of TORI under long-term strategies B1, B2, C2, and C4 were not significantly different than those under Alternative A. Although Alternatives D, E, and G rank the highest with regard to this value (and thus would be expected to have the lowest impact), the minimal differences in the metric values from Alternative A likely indicate that they would not have noticeable impacts on visitor-site interactions.

The difference between the TORI for Alternative F and the other alternatives is largely due to flows during the spring and early summer that are generally at or above 20,000 cfs, while all other alternatives have daily flows that average between 8,000 and 12,000 cfs. Figure H-8 shows the difference in average discharge between Alternative F and the other alternatives. Although Alternative F has very low flows in December and January, the alternative has flows that are more than 7,000 cfs higher than those under other alternatives in spring and early summer months.

TORI values would be higher in years of high volume (>10 maf) when relatively high equalization flows would be implemented according to the Interim Guidelines (Reclamation 2007). However, these relatively high releases result from high inflow volumes in wet years, are unavoidable, and differ little among alternatives.

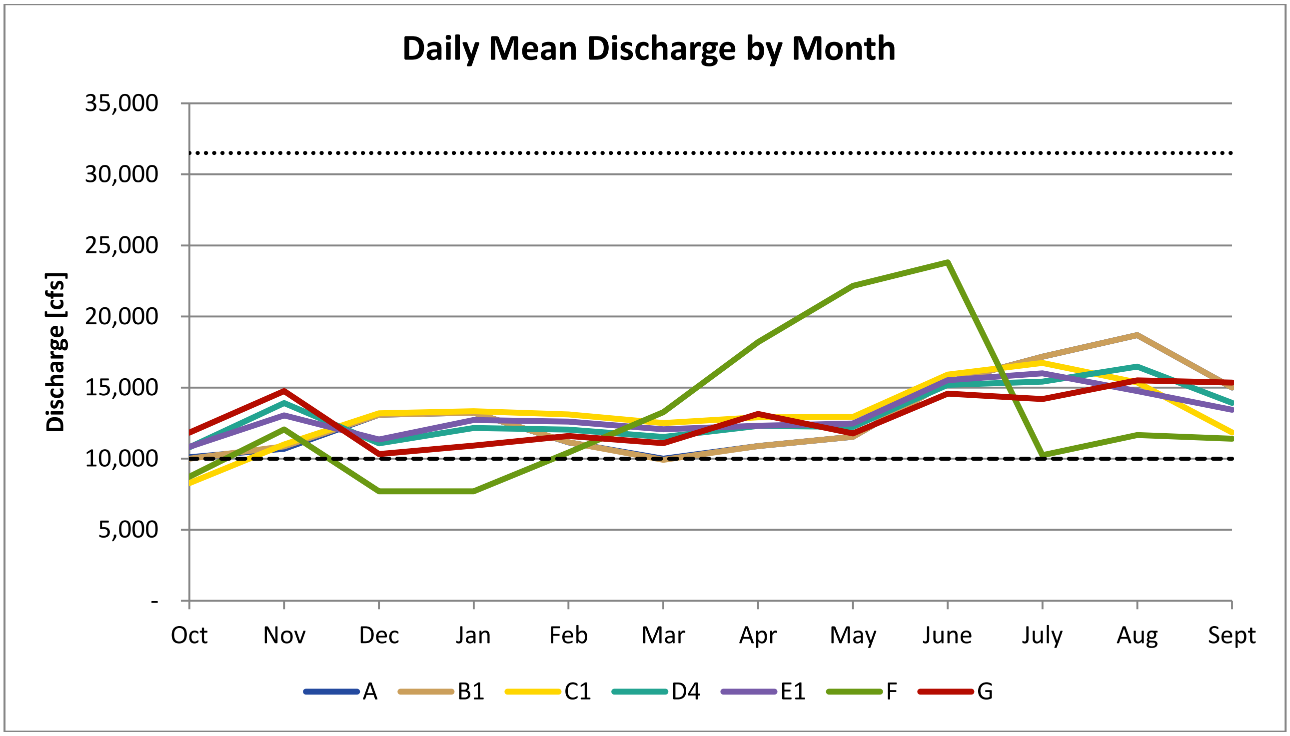

FIGURE H-8 Daily Average Discharge for Representative Long-Term LTEMP Strategies

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