Evolution of the Hoover Dam Inflow Design Flood - A Study in Changing Methodologies

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Abstract

Over the years many changes have taken place in estimating the maximum flood potential at Bureau of Reclamation dams. This paper traces the technological changes by using the Hoover Dam flood studies as an example.

The largest recorded flood in the Black Canyon of the Colorado River, which is the site of Hoover Dam, occurred in July 1884. It was estimated to have a peak discharge of about 300,000 ft^3/s. The Bureau of Reclamation and the Geological Survey determined the magnitude of the 1884 flood based on high water marks in the Black Canyon; flood observations at Lees Ferry; and gage height observations at Grand Junction, Colorado, and Yuma, Arizona. The five-month volume of the flood was estimated to be about 30,000,000 acre-feet. The 1884 flood was considered a “near maximum flood” and became the basis for the design of the spillways and flood control space in Hoover Dam.

In 1990 the Bureau of Reclamation revised the probable maximum flood studies for the Colorado River basin and for Hoover and Glen Canyon Dams. The Dam Safety Office identified the need for the study when flood operations during the 1983 flood required operating the spillways and resulted in considerable damage to the concrete lining of the spillways. The flood hydrology data used for the original dam design were not found to conform to current technical methodology for estimating the probable maximum flood.

New hydrologic studies were conducted using a hydrologic model to convert precipitation to runoff. The design storm was developed from historical storm data that indicated the possibility of two large rain events occurring within a few days of each other. For Hoover Dam the most critical situation could occur in August, when a Pine and Cedar Mountains centered storm follows a San Juan Mountains centered storm by seven days. This storm sequence would produce a probable maximum flood at the dam with a peak discharge of 1,130,000 ft^3/s and a 60-day volume of 9.3 million acre-feet.

Oftentimes, technological change has resulted in the need to modify dams to ensure public safety. In this case, routing the probable maximum flood through Lake Mead does not overtop the dam and results in a maximum water surface that is still three feet below the top of the parapet wall. However, about 100 of Reclamation's dams are unable to safely accommodate the probable maximum flood.

Introduction

A large flood resulting from late season snowmelt in the spring and summer of 1983 required operation of the Hoover Dam spillways. During this operation, damage to the concrete lining of the spillways occurred, leading to the assessment of potential modifications to alleviate the problem. As a part of this analysis, the Flood Section of the Bureau of Reclamation evaluated the adequacy of the hydrologic engineering aspects of the dam. Additional high runoff occurrences in 1984 and 1986 kept the flood issues at Hoover Dam in the forefront.

Upon reevaluation, the hydrologic data used as a basis for sizing the dam, the outlet works capacity, and the allocated flood storage/surcharge space were not found to conform to the current state-of-the-art with respect to operational criteria and technical methodologies. These data also do not reflect recent hydrologic and meteorological data acquired since the original design was completed. Previous design flood investigations were crudely developed from high water marks left from large historical flood events. More recent investigations account for the effects of upstream basin development and reservoir regulation, as well as the knowledge gained from the many large storms that have occurred over the basin since the dam was built.

Basin Description

The Colorado River above Hoover Dam drains an area of 167,000 mi^2. The drainage basin includes parts of Wyoming, Colorado, Utah, New Mexico, Arizona, and Nevada. Approximately 108,000 mi^2 of the drainage basin are above Glen Canyon Dam.

Many dams and reservoirs have been constructed in the basin over the years. The larger reservoirs are formed from water impounded by Fontenelle, Flaming Gorge, Blue Mesa, Morrow Point, Crystal, Dillon, Navajo, Glen Canyon, and Hoover Dams.

The basin is arid to semi-arid with an average annual rainfall of about 10 inches. The annual precipitation varies from over 40 inches in the higher mountainous areas to less than 3 inches near Hoover Dam. Long cold winters and cool short summers characterize the climate of the mountains in the basin. In the lower areas the winters are mild and short, and the summers are long and warm. The temperature extremes in the basin range from –45/C to 46/C. The average annual runoff is less than 1.5 inches for the entire basin. Most of this runoff is produced in the upper basin areas. Snow accumulation normally begins in October in the high mountains and in some years continues through May.

Basis for Original Spillway Design

Hoover Dam (also known as Boulder Dam) was sized using streamflow records in existence prior to 1929. Reliable recorded streamflow records for the Colorado River at Yuma, Arizona began in 1902. Less reliable gage heights were also available at the Yuma site for the earlier period from 1878 through 1901. The largest recorded flow was 210,000 ft^3/s on June 26, 1920. The maximum historic discharge, since the river was first occupied by civilized man in 1856, was believed to have occurred in the summer of 1884 and was estimated to range from 250,000 to 350,000 ft^3/s.[1]

On the basis of the flood data and other safety considerations, a spillway capacity of 400,000 ft^3/s with the reservoir water surface at the crest of the dam (elevation 1232.0 feet) was provided to prevent any possibility of the dam being overtopped by an unprecedented future flood. The total discharge capacity of the dam was 520,000 ft^3/s, which included the spillway capacity along with the outlet works release capacity of 100,000 ft^3/s and the power plant release capacity of 20,000 ft^3/s.[2]

The total reservoir capacity is 30.5 million acre-feet, which includes 9.5 million acre-feet of flood control storage. The design and construction reports for the Diversion, Outlet, and Spillway Structures indicate that the intent of the design was to accommodate not only the largest possible flood but also a flood resulting from a dam failure upstream. The report states, "The ponding effect of the flood storage, combined with the 520 thousand second-feet of discharge capacity, provides for an estimated inflow into the reservoir of nearly 1 million second-feet for several days without overtopping the dam. The provision for so large an inflow into the reservoir was based on the criterion that the dam must be entirely safe for any flood condition, even though the flood might be caused by the failure of a dam at some upstream location."[3]

Original Flood Study

E.B. Debler, Hydraulic Engineer with the Bureau of Reclamation, conducted the original flood studies that were used to size the spillways and flood control space for the dam. In 1930 he wrote Hydrology of the Boulder Canyon Reservoir. Data that were used in the analysis consisted of stream gage records, high water marks, and newspaper accounts.[4]

Prior to construction of the many major dams now located in the Colorado River basin, high flows in the lower portion of the basin occurred frequently. Between 1878 and 1929, peak flows were estimated to exceed 100,000 ft^3/s 23 times and 200,000 ft^3/s three times in the vicinity of Hoover Dam. The Geological Survey and Bureau of Reclamation estimated the peak discharge for the 1884 flood as 250,000 and 300,000 ft^3/s, respectively. These estimates were based on high water marks in the Black Canyon, gage heights at Grand Junction and Yuma, newspaper accounts, and a flood observation at Lees Ferry.[5]

The Geological Survey estimated that the 1884 flood had a peak of 250,000 ft^3/s at Lees Ferry. A high water mark given by a local resident was compared with gage heights for the Lees Ferry gage. The rating curve that was used is unknown. Since the largest gaged flow at this site was 114,000 ft^3/s, the rating curve that was provided by the Geological Survey for this station was extended to estimate the 1884 peak. Several extension techniques were explored to try to reproduce the Geological Survey flood estimate. Reclamation engineers could get close to their estimate but could not reproduce it. Therefore, Reclamation decided to develop its own estimate of the 1884 flood.[6]

Newspapers of 1884 contain numerous references to heavy snows throughout the basin. The Gunnison Daily Review Press reported in mid-May snow from two to five feet deep at several locations between elevations of 9,000 and 10,000 feet. The normal snow depth for the Gunnison watershed was about 18 inches for the end of April. Other newspaper accounts indicated that this condition was widespread over the upper basin.[7]

Only one precipitation station was available for the upper basin in 1884. It was located at Fort Lewis, La Plata County, in the San Juan basin. At this station precipitation was about 40 percent above normal from October through May, and temperatures were below normal during the spring months.[8]

Flows in upstream tributaries were at all-time highs. The Gunnison River, Colorado River at Fruita, and Green River at Green River were at their highest known stages in 1884 and were reported in 1929 as the highest of all time. High flows were also reported in Utah by the Salt Lake City newspapers. Inhabitants reported that high flows continued for weeks.[9]

Based on these accounts and various flow records, Reclamation concluded that the peaks at Green River, Utah and on the Colorado River at Fruita occurred simultaneously. Mr. Robert Follansbee, District Engineer with the Geological Survey, estimated the flow at Fruita to be 125,000 ft^3/s and at Green River to be 95,000 ft^3/s. After making an allowance for the lower streams, the discharge at Black Canyon was estimated as 300,000 ft^3/s.[10]

To check the 1884 flood peak Reclamation used the gage height at Yuma and channel cross section to compute the associated discharge. Based on 1920 and 1921 flow velocity data, a mean velocity of 7.2 ft/s was used for the hydraulic calculations. The discharge was estimated as 250,000 ft^3/s at Yuma. Since flows at Black Canyon were greater than at Yuma due to channel storage in the lower reaches, the Yuma discharge was increased by 19 percent to arrive at the Black Canyon discharge of 300,000 ft^3/s.[11]

Flows, which formed the basis of a flood frequency analysis, were estimated at Black Canyon using data from the gages at Yuma, Topock, Hardyville, Boulder Canyon, Bright Angel, Lees Ferry, and some unidentified main tributaries. Empirical relationships were used to transfer peak flows to Black Canyon. Flows for 1878 through 1901 were solely based on the flow at Yuma. Later years, 1902-1929, relied on comparisons between gages and considerable engineering judgment to develop the annual peaks at Black Canyon. The flow data were plotted on probability paper using methods developed by H. Alden Foster and R.D. Goodrich. The results are shown on Table 1. The 1884 flood was determined to be about a 500-year flood.[12]

Table 1 – 1930 Flood Frequency Analysis for Hoover Dam

Source: U.S. Department of Interior, Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams, (Denver, 1990), 9.

Peak Flow (ft^3/s)	Return Period (Years)	Annual Exceedance Probability (Percent)
130,000	5	20.00
160,000	10	10.00
190,000	20	5.00
230,000	50	2.00
260,000	100	1.00
320,000	500	0.20
360,000	1,000	0.10
450,000	10,000	0.01

The volume of the 1884 flood was estimated as 30,450,000 acre-feet for the period May 3 through August 22. Flow records were reconstructed for the Yuma gage to develop the volume estimate. When the inflow design flood was developed, the duration of the flood was extended to include April through the end of August by using comparisons with other high runoff years. Table 2 displays the monthly volumes of the inflow design flood. As indicated on the table, the inflow design flood volume increased to 33,200,000 acre-feet after adding additional spring flows and extending the period from April through August.[13]

Table 2 – 1930 Inflow Design Flood Volumes for Hoover Dam

Source: U.S. Department of Interior, Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams, (Denver, 1990), 10.

Month	Volume (Acre-feet)	Mean Monthly Flow (ft^3/s)
April	2,000,000	33,610
May	5,000,000	81,320
June	11,850,000	199,160
July	11,350,000	184,590
August	3,000,000	48,790
Total	33,200,000	

1990 Probable Maximum Flood Study

Reclamation revised the inflow design flood for Hoover Dam in 1990. Meteorological studies were conducted by Morrison-Knudsen Engineers and are documented in the report entitled, Determination of an Upper Limit Design Rainstorm for the Colorado River Basin Above Hoover Dam. Reclamation performed the hydrologic analysis, and the results of this study are documented in the report, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams. The following sections of this paper describe these studies in more detail.[14]

Meteorological Analysis

Modern procedures for developing a probable maximum flood involve development of the probable maximum precipitation (PMP) and rainfall-runoff modeling. Probable maximum precipitation is generally defined as “theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year.” Traditionally, the PMP storm is developed by transposing moisture maximized storms to various locations in the basin. Then differences in orographic effects between the storm location and the selected storm centerings are accounted for either by a transposition index or by storm separation techniques. For Hoover Dam, a slightly different approach was taken due to the very large drainage area, extreme variation in orographic effects, and deficiency of large-area storms.[15]

Upper limit design rainstorms (ULDRS) were developed for three locations in the Colorado River drainage above Hoover Dam. The term, ULDRS, was used to emphasize that there are differences in the procedures used to develop these storms from those used to develop the traditional PMP for smaller area sizes. Specific storm analyses involved determination of the ULDRS magnitude, spatial and temporal distributions, storm sequencing, and seasonal variation.[16]

As with any study of this nature, it was first necessary to assemble an exhaustive listing of all known major storms that have occurred in or near the region surrounding the Colorado River Basin above Hoover Dam. Due to the large drainage area and the availability of extreme precipitation estimates from Hydrometeorological Report No. 49 for areas less than 5,000 mi^2, the search for critical storm data concentrated on finding severe rainfall events covering larger areas. Of the 20 storms for which detailed meteorological investigations were performed, 13 storms were analyzed to provide the necessary depth-area-duration data.[17]

Since the study basin is located in a region of complex topography, which produces a significant effect on total storm rainfall, it was necessary to estimate likely storm centerings and associated “generic” isohyetal patterns prior to development of the ULDRS. An important consideration in the development of likely storm centerings was the location of Glen Canyon Dam in relation to Hoover Dam. The objective was to provide the necessary design storms that would affect not only Hoover, but also the two dams operating in combination. Examination of the isohyetal patterns of rainfall associated with major storms occurring in the drainage were particularly useful in identifying three storm centerings and their related isohyetal patterns. The three storms were located in the San Juan Mountains (Colorado), Boulder Mountains (Utah), and Pine and Cedar Mountains (Utah).

The ULDRS magnitude for each of the three storm centerings was evaluated by two separate methods. The first approach is commonly referred to as the storm separation method, where observed areal storm precipitation is separated into components (convergence and orographic). Each precipitation component is treated and evaluated separately, and later recombined, to provide total design storm precipitation. The second approach used the traditional method of storm moisture maximization and transposition. After evaluation of the assumptions and uncertainties involved in application of each approach, the results were averaged to produce the final ULDRS magnitude.

Due to the large basin and storm areas involved, it was necessary to describe the spatial distribution of average areal ULDRS precipitation. Hydrologic trials were conducted using preliminary average areal precipitation. A storm area of 40,000 mi^2 was critical for development of the maximum inflow to Hoover Dam. The ULDRS magnitude was estimated as averaging from 6.93 to 7.29 inches in depth for 72-hour storms for the three locations.

Critical inflow to the dams could result from a series of storms occurring in sequence.

Investigations were conducted to define the relationship between storm magnitude and dry-period interval separating the sequenced storms. A relationship between the days separation between storms, and the magnitude of areal rainfall both prior and subsequent to the main storm was developed.

To adequately assess the flood potential, it was necessary to define the magnitude of the ULDRS event for the period from May through October. It is during this period that the greatest flood threat on the Colorado River above Hoover Dam would likely result from the combination of the ULDRS event with the snowmelt hydrograph. The ULDRS event for all three centerings could occur with the same magnitude during the period from August 1 through October 31. Prior to August, the seasonal variation of the ULDRS would indicate a decrease in rainfall potential.

Hydrologic Analysis

Selection on an inflow design flood (IDF) is generally based on an incremental hazard evaluation downstream for the dam. "The IDF is the flood flow above which the incremental increase in water surface elevation downstream due to failure of a dam or other water retaining structure is no longer considered to present an unacceptable additional downstream threat." In this case, the probable maximum flood (PMF) was selected as the inflow design flood because if the dam failed, it would result in catastrophic consequences, including loss of life. The PMF is defined as "the maximum runoff condition resulting from the most severe combination of hydrologic and meteorologic conditions that are considered reasonably possible for the drainage basin under study."[18]

Reclamation used the Flood Hydrograph and Routing (FHAR) computer program to convert excess precipitation to runoff and generate the flood hydrograph for the ULDRS. FHAR, which was developed by Reclamation, uses unit hydrograph theory. The program derives the flood hydrograph by applying increments of excess precipitation to the unit hydrograph. The unit hydrograph is computed from the dimensionless graph, given the basin area, lag time, and unit time.

The lower and upper basins were divided into 99 subbasins for the analysis. In general, subbasin delineation was made by following major tributary boundaries. Subbasins that had similar characteristics of elevation, slope, land use, and drainage pattern were combined where possible. The size of the subbasins was limited to areas of less than 5,000 mi^2.

Field trips were made to become familiar with the subbasins. Soil and geologic conditions, land use, vegetation type and cover, and basin roughness and steepness were examined to better estimate loss rates and lag coefficients. These observations were used for all subbasins visited.

Loss rates are a measure of the precipitation lost to infiltration, evaporation, transpiration, absorption, and minor depression storage in the basin. In general, the lower basin near Lake Mead and the north-side tributaries to the lake are areas of low infiltration and are subject to flash flooding. The other areas and tributaries, especially Kanab Creek, Kaibab Creek, and most of the Little Colorado River basin had somewhat higher loss rates. In these areas, the vegetative cover was heavier, and the loss rates appeared to increase with elevation rise. Most of the Little Colorado River basin showed very little evidence of flash flooding or stream channel development.

In the upper basin, those areas tributary to Lake Powell were very desert-like and exhibited signs of flash flooding. The loss rates appeared quite low, and the vegetative cover was very sparse. Some portions of the lower Green River subbasin had extensive outcrops of Mancos Shale. The upper basin areas exhibited a similar increase in vegetation and loss rates with elevation rise.

In applications of the unit hydrograph approach, the Reclamation lag equation is used in determining the lag time of the flood hydrograph. Lag time is defined as the time from the center of mass of unit rainfall excess to the time that one-half the volume of unit runoff from the drainage basin has passed the concentration point. The lag coefficient is a measure of the hydraulic efficiency of a basin to transmit water, which reflects overall basin roughness, steepness, and vegetative cover. Lag coefficients for the basins above Hoover ranged from 1.3 to 5.5.[19]

The dimensionless unit hydrograph was used to calculate the flood hydrograph for each subbasin. The basin above Hoover Dam includes three basic types of terrain – deserts, foothills, and mountains. Data gathered from the field reconnaissance and from analysis of basin features shown on topographic maps were compared with similar data for basins where unit hydrographs had been developed from observed flood hydrographs. Separate dimensionless graphs were used for each type of topography. The following three dimensionless graphs were used in the study: (1) Salt River for the desert areas, (2) Buckhorn for the foothill areas, and (3) Uinta for the mountainous areas.[20]

The Tatum method was used to route flood hydrographs from one subbasin to the next downstream subbasin, and to combine them with additional flood hydrographs as the floods move downstream. The Tatum method is a successive average lag procedure. It is commonly used to route hydrographs through channels, which have no appreciable storage or large tributary inflows, or where costs of obtaining channel cross-section and other data needed for more sophisticated methods are prohibitive. FHAR uses the modified Puls method to route floods through reservoirs or through short stream reaches in which the time of travel and wedge storage is negligible.

Antecedent Flood

The antecedent flood is that flood, and associated climatic conditions, affecting the basin prior to the onset of the upper limit design rainstorm. For this study, the antecedent flood is a 100-year snowmelt event. This flood is not nearly as large as what might be expected as the probable maximum snowmelt flood, but the volume is still very large when compared to the volume of the ULDRS flood event. In order to model operations of the reservoirs of the Colorado River above Hoover Dam, daily flows were required for a complete calendar year. The 100-year base snowmelt flood, which was developed statistically, had an annual volume of 25,375,000 acre-feet into Lake Powell and 1,281,000 acre-feet as intervening flow into Lake Mead from the contributing drainage area downstream of Lake Powell.

Reservoir Operations

The reservoirs in the Colorado River basin are operated as an integrated system. The system has a total flood control space requirement of 5,350,000 acre-feet, which must be evacuated from storage by January 1. At least 1,500,000 acre-feet of that space must be in Lake Mead, which is the only facility in the system with exclusive flood control space. One of the primary goals of the flood control operations for the Colorado River system is to keep the exclusive flood control storage at Hoover vacant year-round to regulate potential rain floods.[21]

The 1982 field working agreement between Reclamation and the Corps of Engineers for flood control operations of Hoover Dam and Lake Mead establishes the reservoir operating criteria. Two sets of operating rules are used to operate the system. During the space-building or drawdown season, which extends from August through December, the objective is to gradually drawdown the reservoir system to create space for next spring's snowmelt runoff. During the runoff forecast season, from January through July, the forecasted maximum inflow hydrograph is routed through the reservoir using predetermined release rates, so that the reservoir system is full by July1.[22]

Using the 100-year snowmelt flood values, routing studies were performed to simulate reservoir operations during the antecedent flood event. The Colorado River system operation was modeled bimonthly beginning January 1 to reflect proper operations during a forecasted 100-year snowmelt flood. Runoff forecast errors were subtracted from the actual inflows through July 31 in order to make operational decisions that reflect a reasonable degree of conservatism. The results of these investigations produce the starting elevations that were required to route the ULDRS flood event.

Probable Maximum Floods

Determination of the probable maximum floods for Hoover Dam involved generating seasonal flood hydrographs by applying the results of the meteorological investigation. Numerous combinations of ULDRS centerings and storm separations were evaluated to determine the most critical hydrologic conditions for the dam. The ULDRS flood hydrographs were combined with the snowmelt antecedent flood to determine the most critical hydrologic condition at the dam. Results of these analyses produced PMFs for the critical May through August storm season.

The most critical flood situation for Hoover Dam occurs when the San Juan storm is followed by the Pine and Cedar Mountain storm. The flood hydrographs developed for the upper basin were routed through Glen Canyon Dam, and combined with concurrent runoff and intervening base flow hydrographs for the area between Glen Canyon and Hoover Dams. The resulting PMF had a peak inflow of 1,130,000 ft^3/s and a 60-day volume of 9.3 million acre-feet.[23]

Discussion

Reclamation's approach toward estimating the inflow design flood for Hoover Dam has changed dramatically over the years, moving from simple hand calculations to more complex computer simulations. The original flood study for Hoover Dam relied on high water marks and gage heights to construct the largest possible flood for design. The analysis assumed that the largest flood had already occurred in the basin and was reflected in the historical record. Even today, the 1884 flood is still the largest flood on record in this basin. When put in a statistical context, it was estimated to have a return period of about once in 500 years. By modern standards, this is considered an unsafe design standard. However, the engineers that designed the dam sized the spillways and outlet works to pass the peak of this flood without taking credit for the additional flood regulation provided by the storage space in the reservoir. These very conservative design decisions produced a dam that is still safe when tested against today's design criteria.

The magnitude of the differences between the two studies can be determined by comparing the peak discharge and the 60-day volumes. The 1930 flood study produced an inflow design flood with a peak discharge of 300,000 ft^3/s and an approximate 60-day volume of 23,200,000 acre-feet. The 1990 PMF had a peak discharge of 1,130,000 ft^3/s and a 60-day volume of 9,300,000 acre-feet. So even though the peak discharge of the 1990 PMF is nearly four times as large as the 1930 IDF, the volume is less than half the 1930 volume.

An additional 60 years of data have been collected since the 1930 study was completed. Because PMF procedures attempt to produce the maximum flood possible at a site, one would expect additional data to result in larger flood values in the 1990 study. Since most of the volume comes from snowmelt, one could speculate that the 1884 flood was predominately a snowmelt flood with a return period much greater than the once in 100 years, which was used as the antecedent flood in the 1990 study. This could account for the smaller peak and larger volume in the 1930 analysis.

The dams and reservoirs that have been built upstream of Hoover could also be responsible for some of the volume differences. Hoover Dam was one of the first major structures on the Colorado River. The other large dams, which were built after 1930, can store much of the flood volume. Normal reservoir operations use flood forecasting to regulate snowmelt floods by vacating reservoir storage prior to the occurrence of the flood peak. This helps maximize power generation and minimize flood damages in the basin, and reduces the volume of water into Lake Mead.

Since Hoover Dam was built, engineers and hydrologists have collected a lot of data and gained additional understanding of meteorological, hydrologic, and statistical processes. Climate and streamflow data available for analysis has increased dramatically in both quantity and quality. Computer technology now allows analysis of detailed storm patterns and construction of rainfall-runoff models in order to obtain a better understanding of the hydrology of the Colorado River. This allows the engineer to run numerous computer simulations to determine the most critical hydrologic condition for the dam.

[1.] U.S. Department of Interior, Bureau of Reclamation, Diversion, Outlet, and Spillway Structures, Boulder Canyon Project Final Reports, Part IV-Design and Construction, Bulletin 3, (Denver, 1947), 255.

[2.] Bureau of Reclamation, Diversion, Outlet, and Spillway Structures, 255.

[3.] Bureau of Reclamation, Diversion, Outlet, and Spillway Structures, 255.

[4.] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, Bureau of Reclamation, U.S. Department of Interior, (1930).

[5.] U.S. Department of Interior, Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams, (Denver, 1990), 9.

[6] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 36-37.

[7] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 39.

[8] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 39.

[9] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 39-40.

[10] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 40.

[11] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 40-43.
.

[12] Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 24-34.

[13] Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams, 10; Debler, E.B., Hydrology of the Boulder Canyon Reservoir, 198.

[14] Morrison-Knudsen Engineers, Inc., Determination of an Upper Limit Design Rainstorm for the Colorado River Basin Above Hoover Dam, Bureau of Reclamation, U.S. Department of Interior, (Denver, 1990); Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams.

[15] Cudworth, A.G., Flood Hydrology Manual, Bureau of Reclamation, U.S. Department of Interior, (Denver, 1989), 25.

[16] Morrison-Knudsen Engineers, Inc., Determination of an Upper Limit Design Rainstorm for the Colorado River Basin Above Hoover Dam, xi-xii.

[17] Hansen, E.M., F.K. Schwarz, and J.T. Riedel, "Probable Maximum Precipitation Estimates – Colorado River and Great Basin Drainages," Hydrometeorological Report No. 49, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, (Silver Spring, 1977); Morrison-Knudsen Engineers, Inc., Determination of an Upper Limit Design Rainstorm for the Colorado River Basin Above Hoover Dam.

[18] Interagency Committee on Dam Safety, Federal Guidelines for Dam Safety: Selecting And Accommodating Inflow Design Floods for Dams, Federal Emergency Management Agency, (1998), 1; Cudworth, A.G., Flood Hydrology Manual, 114.

[19] Cudworth, A.G., Flood Hydrology Manual, 68-71.

[20] Cudworth, A.G., Flood Hydrology Manual, 90-95.

[21] U.S. Army Corps of Engineers and Bureau of Reclamation, Colorado River Basin – Hoover Dam - Review of Flood Control Regulation – Final Report, U.S. Army Corps of Engineers, Los Angeles District, Bureau of Reclamation, Lower Colorado Region, (1982).

22. U.S. Army Corps of Engineers and Bureau of Reclamation, Colorado River Basin – Hoover Dam - Review of Flood Control Regulation – Final Report.

23. Bureau of Reclamation, Colorado River Basin Probable Maximum Floods - Hoover and Glen Canyon Dams, 86.