COLORADO RIVER BASIN
PROBABLE MAXIMUM FLOODS
HOOVER AND GLEN CANYON DAMS

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SUMMARY

High runoff from the late season melt of the snowpack in the spring and summer of 1983 resulted in the first nontest operation of Glen Canyon Dam's spillways since they were placed in operation in 1964. During these operations, cavitation caused severe damage to the concrete lining of the spillways, leading to the Bureau of Reclamation's (Reclamation) assessment of potential modifications to correct the problem. The spillways at Hoover Dam were also damaged from flood releases during 1983. As a part of dam safety investigations, Reclamation computed probable maximum floods for each structure in the following manner.

Upper Limit Design Rainstorms (ULDRS) were developed for three locations in the Colorado River drainage above Hoover Dam. For each location, the rainfall magnitude, spatial and temporal distributions, and seasonal variations ' were determined from transposed and moisture maximized historical events. Storms ranging in size from 5,000 to 100,000 square miles were tested in the hydrologic computer model to arrive at the 40,000-square-mile critical storm area. The magnitude of ULDRS was estimated as averaging from 6.93 to 7.29 inches in depth for 72-hour storms for the three locations. Historical storm data indicated the possibility of two large rain events occurring within a few days of each other; therefore, design storm sequences were developed that incorporated two ULDRS or near-ULDRS events.

The 100-year snowmelt event was selected as the antecedent flood affecting the basin prior to the onset of the ULDRS. A statistical analysis of floodflows was the basis for developing the daily undepleted snowmelt base flood, which had an annual volume of 26.7 million acre-feet at Hoover Dam. Approximately 3.6 million acre-feet of depletions were subtracted from the snowmelt flood to account for present streamflow regulation and use in the upper basin.

A hydrologic model was developed to convert excess precipitation to runoff and to generate the flood hydrographs. Input to the model consisted of the system configuration, rainfall, lag times, loss rates, dimensionless unit hydrographs, and starting reservoir elevations. The 167,000-square-mile drainage basin above Hoover Dam was divided into 99 subbasins, of which 65 were above Glen Canyon Dam. Starting reservoir elevations for the major dams upstream from Glen Canyon were determined by simulating forecasted inflow conditions and routing the 100-year snowmelt flood through the facilities. Release decisions were based on current flood control operating criteria for the Colorado River reservoir system.

The most critical flood condition for Glen Canyon Dam occurs in August. A San Juan Mountains storm, followed a day later by a Boulder Mountains storm, produces the largest flood at Lake Powell. This probable maximum flood for Glen Canyon Dam has a peak inflow of 697,000 ft3/ s and 60-day volume of 5.8 million acre-feet. Routing this flood through the reservoir results in a maximum water surface elevation of 3,709.8 feet, which is more than 5 feet below the dam crest elevation.

At Hoover Dam, the largest flood occurs in August, when a Pine and Cedar Mountains storm lags seven days after the San Juan Mountains storm. This probable maximum flood at the dam has a peak inflow of 1,130,000 ft-'Is and 60-day volume of 9.3 million acre-feet. When this flood is routed through Lake Mead, the maximum reservoir elevation reaches 1,233.0 feet, still 3 feet below the top of the parapet.

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LIST OF ACRONYMS

CRSS	Colorado River Simulation System
DAD	Depth-Area-Duration
FHAR	Flood Hydrograph and Routing
HYPO-ULDRS	Hypothetical-Upper Limit Design Rainstorm
MKE	Morrison-Knudsen Engineers
NWS	National Weather Service
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
POS	Plan of Study
Reclamation	Bureau of Reclamation
SEED	Safety Evaluation of Existing Dam&
ULDRS	Upper Limit Design Rain Storm
USGS	U.S. Geological Survey

1.0 INTRODUCTION

1.1 AUTHORITY AND BACKGROUND

The Bureau of Reclamation (Reclamation) Safety Evaluation of Existing Dams (SEED) program provides the authority for updating hydrologic studies for Hoover and Glen Canyon Dams. Discussions with Reclamation's Division of Dam Safety and Division of Water and Land Technical Services were initiated in January 1986 to begin activities related to the probable maximum flood (PMF) study. The need for the study was initially identified by the Division of Dam Safety when consideration was given to replacing the needle valves at Hoover Dam. Funds for the study were obligated from several sources, including Colorado River Storage Project revenues and SEED funds.

High runoff from a late season melt of the snowpack in the spring and summer of 1983 resulted in 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 adequacy of the hydrologic engineering aspects of the dam were evaluated. Additional high runoff occurrences in 1984 and 1986 have kept the flood issues at Hoover Dam in the forefront. Concern has also been expressed about lesser magnitude floods (e.g., 25-, 50-, and 100-yr frequency floods) as they may affect the current operation at Hoover Dam.

That same year, 1983, also contributed a record inflow to Glen Canyon Dam. These record inflows caused Lake Powell to be at or above surcharge (elevation 3700 feet, 27,000,000 acre-feet) for 3.5 months. Extensions were added to the spillway gates at the dam to accommodate the high inflows and resulting high reservoir water surface elevations. The spillways were operated in the first non-test situation since Glen Canyon Dam was completed in 1964. This operation caused severe cavitation in the spillways. After the flood peak had passed, and the flood danger subsided (July 1983), repairs on the spillways began. High inflows in the following year also occurred. The spillways and power and river outlet works, in combination with reservoir storage, were able to control and pass these high inflows without damage occurring to the spillways.

The flood hydrology data used as a basis for sizing the dams, the outlet works capacity, and the allocated flood storage/surcharge space were found not 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 meteorologic 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. This flood investigation accounts for the effects of upstream basin development and reservoir regulation, as well as the knowledge gained from many large storms which have occurred over the basin since the dams were built.

Determination of the PMF for Hoover requires that the design storm be located either in the basin between Hoover and Glen Canyon Dam or in the basin above Glen Canyon Dam. Hoover and Glen Canyon Dams, as well as other upstream dams, are operated as a part of the Colorado River system of reservoirs. The PMFs were developed for both dams in this study.

Personnel of the Flood Section of Reclamation's Denver Office concluded that the design scenario required to produce a reasonable probable maximum flood inflow to these dams would include four specific conditions. These are: (1) the accumulation of an optimum snowpack over the Colorado River Basin during the preceding winter and spring, with low temperatures and continued snowpack accumulation into the late spring; (2) high levels of ground wetness and river flow occasioned by a preceding high runoff year; (3) rapid snowmelt resulting from relatively high temperatures following the snowpack accumulation season; and

(4) the occurrence of a design storm (which may be comprised of a series of storm events) during the recession limb of the snowmelt runoff hydrograph.

1.2 STUDY SCOPE AND PARTICIPANTS

The preliminary work on the PMF study began in January 1986: In a normal situation the development of design storm data would be conducted by the Flood Section at the Denver Office of the Bureau of Reclamation. The Flood Section, however, was not able to complete the necessary meteorology to determine the probable maximum precipitation (PMP) for the study area within scheduled time frames because of commitments to other on-going studies. Therefore, meeting those time frames required the services of an Architect/Engineer firm staffed with professional engineering personnel that had knowledge of development of such design data. Steps were taken to identify and acquire the services of a consulting firm with the necessary expertise. Using the Lower Colorado Region's indefinite quantity contract with Morrison-Knudsen Engineers (MKE), the services of qualified hydrometeorologists were obtained.

A task order was issued in April 1986, to MKE to develop a Plan of Study (POS) to acquire the necessary hydrometeorological design data for Hoover Dam. The POS was completed on July 1, 1986, for $34,700. The POS identified five study parts estimated to cost about $990,000 and would require nearly 3 years to complete. The five parts were:

1. Initial Project Specifications.
2. Phase I - Optimum Snowpack Accumulation and Critical Melt Criteria.
3. Phase II Development of Upper Limit Design Rain Storm(s) (ULDRS).
4. Phase III Need for and Determination of Storms Less Than ULDRS (for use in combination with Phase I).
5. Phase IV - Evaluation of Less Than Optimum Snowpack for Use in Combination with ULDRS.

The five study parts were examined in detail, and the implications of doing or not doing some of the phases or portions thereof were thoroughly explored. Phase II was considered most important because the current criteria available for developing probable maximum precipitation in the study area are limited to watersheds with drainage areas less than 5,000 square miles. The total cost of determining the PMF, including all five parts of the meteorologic investigation and the accompanying hydrologic studies, would be approximately $1,250,000 and would require about 3.5 years to complete. Because of the high estimated study cost, an alternative method for determining the snowpack and snowmelt runoff was developed. Phase II and the initial project specifications were the only portions of the POS undertaken. The Hoover Dam and Glen Canyon Dam PMF study combines the design rainstorm (ULDRS) and the 100-yr snowmelt flood to obtain an estimate of the PMF.

The hydrology study began in January 1987 and involved active participation by Reclamation's Lower Colorado and Upper Colorado Regions and Denver Office and by Morrison-Knudsen Engineers. Study leadership was provided by the Flood.Section at the Denver Office.

A field reconnaissance of the subbasins around Lake Mead and upstream of Lake Powell was completed in June 1987. The regional hydrology staffs were responsible for subbasin delineation and map preparation, and assisted in subbasin hydrologic parameter estimation. The Upper Colorado regional staff prepared the, preliminary data for the 100-yr snowmelt flood analysis. All of the offices played a role in preparing the necessary computer files and data for testing and final use of the meteorological analysis.

1.3 BASIN DESCRIPTION

The Colorado River above Hoover Dam drains an area of 167,000 square miles. The drainage basin includes parts of Wyoming, Colorado (western half), Utah (eastern half), New Mexico, Arizona, and Nevada, as shown on figure 1.1. Approximately 108,000 sq. mi. of the drainage basin are above Glen Canyon.

The river originates in the Rocky Mountains *of* Colorado and Wyoming and flows south-southwest about 800 river miles to Hoover Dam. The basin is about 600 miles in length from its northern boundary in the Wind River Range in Wyoming to its southern boundary at Hoover Dam and varies in width from 300 miles in the upper section to 500 miles in the lower section.

The basin boundary consists of mountains that are 13,000 to 14,000 feet high in Wyoming, Colorado, and Utah; the boundary drops to elevations of less than 1,000 feet at Hoover Dam. The northern portion of the basin, in Colorado and Wyoming, is a mountainous plateau that ranges 5,000 to 8,000 feet in elevation. This plateau encompasses deep canyons, rolling valleys, and intersecting mountain ranges. The central and southern portions of the basin, in eastern Utah, northwestern New Mexico, and northern Arizona, consist of rugged mountain ranges interspersed with rolling plateaus and broad valleys. In general, the mountains in the southern part of the basin are much lower than those in the northern part. Much of the interior basin consists of plateaus that range from 5,000 to 8,000 feet in elevation. The entire basin averages about 6,700 feet in elevation. The portion of the basin above Glen Canyon Dam averages about-7,400 feet in elevation.

The Colorado River and its principal tributaries flow mostly in deep canyons. The Green River, the largest tributary, flows through similar canyons in Wyoming, Colorado, and Utah. The Yampa, White, Duchesne, Price, and San Rafael Rivers, flow through canyons and rolling hills to the Green River. The Gunnison and Dolores Rivers drain much of western Colorado prior to joining the Colorado River. The San Juan River drains mountains and plateaus in southwestern Colorado, northwestern New Mexico, and northern Arizona, and flows through a large canyon in southern Utah to join the Colorado River in Lake Powell. Below Glen Canyon Dam, the Colorado River flows through Marble Canyon and Grand Canyon and then into Lake Mead. The Little Colorado River joins the Colorado River in this lower area. It flows through wide valleys and some canyon areas in its upper reaches and then enters a broad, low-walled, sandy channel in the middle reaches. In the lower reaches, it flows through a deep canyon until it reaches the Colorado River in Grand Canyon. The Virgin River combines with the Colorado River in Lake Mead.

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. Table 1.1 shows the drainage areas and reservoir capacities for these reservoirs.

Rocks of all geological ages, from the Archean age to most recent alluvial deposits, are found in the Colorado basin. The Rocky Mountains in the basin are composed of granite schists, gneisses, lavas, and sharply folded sedimentary rocks. The high watershed mountains in Colorado (Rocky Mountains), Wyoming (Wind River Mountains), and Utah (Uinta and Wasatch Mountains) have all been glaciated. The geology of the plateau areas in the basins of southwestern Wyoming, eastern Utah, and northern Arizona is primarily horizontal sedimentary rock. There are also many formations of hard sandstone, limestone, and soft shale. Remnants of volcanic activity can also be found in many areas of the basin. The Colorado River and its tributaries have cut narrow, deep canyons into the flat-topped mesas of the basin. The broad Grand Canyon area was carved as the formations arched several thousand feet higher than the surrounding country, and the Colorado River cut through these formations to the ancient underlying granites.

Soils of the basin consist of the remains of the underlying parent rocks found in the basin. The parent materials include limestones, sandy limestones, sandstones, shales, conglomerates, valley and river alluvium, terrace gravels, igneous and metamorphics, and volcanics. The soils include sands, silts, clays, and loams, and vary widely in areal extent and location. Most of the deeper soils are found in the higher elevations in both the lower and upper basins.

Table 1.1.-- Major dams in the Colorado River basin

Dam	River/state year completed	Total reservoir capacity (acre-feet)	Drainage area (sq. mi.)
Fontenelle	Green/Wyoming 1964	345,360	4,200
Flaming Gorge	Green/Utah 1964	3,788,700	15,200
Blue Mesa	Gunnison/Colorado 1966	940,700	3,500
Morrow Point	Gunnison/Colorado 1968	117,200	3,600
Dillon	Blue/Colorado 1963	254,000	335
Crystal	Gunnison/Colorado 1976	25,200	4,000
Navajo	San Juan/ New Mexico 1963	1,708,600	3,600
Glen Canyon	Colorado/Arizona 1963	27,000,000	108,000
Hoover	Colorado/Nevada 1935	29,755,000	167,000

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 -50ºF to 115ºF. 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.

Vegetation varies from typical desert related plants in the lower basin (cactus, Joshua trees, creosote bush, salt bush, greasewood, desert sage, and mesquite), to sage brush and perennial short and semi-desert grasses in the high plateaus, to typical mountainous vegetation (Juniper, Spruce, and Piñon Pine) in the higher portions of the basins. The vegetation density correlates nearly directly with elevation increase (higher elevation means more dense cover). Flooding from snowmelt in the basin normally begins in April and May and reaches its maximum in mid to late June or sometimes in early July, depending on the year. Flooding also occurs as the result of intense thunderstorms over small basins during the summer. Late season (July-October) tropical storms have occurred over large portions of the basin.

1.4 HISTORIC FLOODS IN THE COLORADO RIVER BASIN

The largest recorded flood is that of July 1884, which was estimated to have had a peak flow of about 300,000 ft^3/s on July 7 or July 8, in the Black Canyon of the Colorado, site of Hoover Dam. Estimates of this peak flow have ranged between 250,000 and 350,000 ft^3/s. The 1884 flood had three distinct peaks, the maximum being around 300,000 ft^3/s. Many spring floods in the lower Colorado mainstem tend toward a generally broad shaped hydrograph. The 1884 flood estimate was made by the Bureau of Reclamation and the U.S. Geological Survey (USGS) and was based on gage height observations at Grand Junction, Colorado, and Yuma, Arizona; flood observations at Lees Ferry; and high water marks in the Black Canyon. The volume of the 1884 flood was estimated to be about 30,000,000 acre-feet for a five month period. Some evidence exists of a flood prior to that time, about 1862, that may have been greater, but estimates of its volume have not been made.

On June 18-19, 1921, a flood peak of 220,000 ft^3/s was observed at Lees Ferry. Other major floods of record with flows of over 110,000 ft^3/s occurred in the vicinity of Hoover and Glen Canyon Dams in 1880, 1885, 1886, 1901, 1905, 1906, 1907, 1909 (June and September), 1912, 1914, 1917, 1920, 1922, 1927 (July and September), 1928, 1929, 1941, 1952, and 1957. The flow into Hoover Dam would have exceeded 100,000 ft^3/s in 1983 and 1984 if the upstream reservoirs had not been in place. Between 1878 and 1976 the flow has exceeded 100,000 ft^3/s 31 times and has exceeded 200,000 ft^3/s three times. It has exceeded 50,000 ft^3/s many, many times.

Notable floods on the Colorado River and its tributaries were compiled from USGS Water Supply Paper 918 and other USGS water supply papers. These data were collected at USGS stream flow recording stations and are shown in table 1.2.

Since Hoover Dam was completed in 1935, the largest floods occurred in 1941, 1952, 1957, and 1983. Maximum reservoir inflows were 119,200, 122,000, 124,000, and 94,600 ft^3/s, respectively. Maximum reservoir releases were 35,500, 30,900, 18,400, and 50,800 ft^3/s for each of these years.

Since Glen Canyon Dam was completed in 1963, the largest reservoir inflows occurred in 1983 and 1984. The maximum inflow to Lake Powell was 116,000 ft^3/s in 1983 and 125,600 ft^3/s in 1984. Reservoir releases were limited to a maximum of 97,300 and 44,600 ft^3/s in 1983 and 1984, respectively.

Table 1.2.-- Notable floods on the Colorado River and its tributaries

River/Location	Date	Peak flow (ft3/3)	Drainage area (sq. mi.)
Colorado River	July 4, 1884	[1]125,000	17,800
near Fruita CO	June 16, 1921	81,100	
Colorado River	July 4, 1884	[1]125,000	24,100
near Cisco UT	June 19, 1917	76,800	
Yampa River	May 27, 1984	70,300	3,410
near Maybell CO	June 27, 1983	61,900	
Green River	June 27, 1917	68,100	44,850
near Green River UT	June 17, 1921	65,500	
Lower San Juan River near Ship Rock NM	Oct. 10, 1911	[1]80,000	12,900
San Juan River near Bluff UT	Oct. 7, 1911	85,000	23,000
Colorado River	July 7, 1884	[1]300,000	107,900
at Lees Ferry AZ	June 18, 1921	220,000	
Little Colorado River at Grand Falls AZ	Sept. 19, 1923	120,000	21,200
Virgin River	Dec. 6, 1966	35,200	5,090
at Littlefield AZ	March 3, 1938	22,000	
Colorado River at Grand Canyon AZ	1862	[1]500,000	137,800
Colorado River	June-July 1862	[1]400,000	172,300
at Topock Bridge AZ	July 10, 1884	[1]300,000	
	June 22, 1921	200,000	

[1] Estimated flows from high water marks; actual flows may have been higher.

1.5 PREVIOUS STUDIES

The studies that follow for Hoover and Glen Canyon Dams provide the hydrologic design criteria for the existing facilities. They also establish operating rules for the reservoirs which were used in developing the new PMFs. Each report is listed in approximate order of importance to this investigation. Additional reports are available for other dams within the Colorado River Basin, but have not been summarized here.

1.5.1 Hoover Dam

1. Hydrology of the Boulder Canyon Reservoir, by E. B. Debler, Bureau of Reclamation, January 31, 1930.

This study includes analyses of floods in the Black Canyon, site of Hoover Dam. The results were used to size spillways and flood control space for the dam. Flood frequency analyses were also completed for the dam site. The following paragraphs contain information that was presented in Debler's report.

Prior to construction of Hoover Dam, high flows along the lower Colorado River occurred annually. The 1884 flood had a peak flow between 250,000 and 300,000 ft ^{3}/s, as estimated by the Geological Survey and Bureau of Reclamation, respectively. These estimates were based on gage heights at Grand Junction and Yuma, a flood observation at Lees Ferry, newspaper accounts, and high water marks in Black Canyon. 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 (1884, 1920, and 1921) at Black Canyon.

Newspapers of 1884 contain numerous references to heavy snows and the late arrival of spring, but only one precipitation station was available in the upper basin. The station was located in the San Juan basin at Fort Lewis and showed precipitation 40 percent above normal from October to May, with temperatures below normal in the spring.

Flood waters of the Colorado River appeared in Salton Sink in 1828, 1840, 1849, 1852, and 1867; however, this fact does not necessarily indicate floods greater than 1884. Some evidence indicates, the 1867 flood was probably a high flood, but may not be larger than the 210,000 ft^3/s which occurred in 1921. Changes in stream bed elevation greatly affect gage heights recorded for some of these events.

Debler considered the 1884 event a "near maximum flood." He indicated that with 9,500,000 acre-feet of flood control capacity, reservoir outflow could be limited to 75,000 ft^3/s. The spillways were each sized to pass 200,000 ft^3/s, for a total capacity of 400,000 ft^3/s . The outlet works were sized to pass 100,000 ft^3/s, and the flood control space was set at 9,500,000 acre-feet.

The 1884 flood was determined to be about a 500-year flood. Table 1.3 displays the flood frequency analysis conducted as a part of Debler's study.

Table 1.3.-- 1930 flood frequency analysis for Hoover Dam

Peak flow (ft3/S)	Frequency (year)	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 1884 flood was estimated to have a volume of 30,450,000 acrefeet. The flood occurred from May 3 through August 22. When the inflow design flood was developed, the period of the flood was extended from April through the end of August. The resulting flood hydrograph is quantified in table 1.4 and shown on figure 1.2.

Table 1.4.--Original 1930 inflow design flood hydrograph for Hoover Dam

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
April-August	33,200,000	

2. Review of Flood Control Regulation - Colorado River Basin, Hoover Dam, by Corps of Engineers and Bureau of Reclamation, July 1982.

This report is a review and update of flood information since the closures of Hoover and Glen Canyon Dams. The Corps concluded that, with the reservoir conservation space in the Colorado River Basin now filled, the potential for damaging flood control releases from Hoover Dam exists. For many years the flood control operation plan for Hoover Dam had incorporated a target maximum release of 40,000 ft^3/s. However, encroachment in the floodplain below Hoover Dam has significantly reduced that figure to about 28,000 ft^3/s, which has been estimated as the maximum release that will not damage inhabited structures downstream.

3. Boulder Canyon Project Final Reports, Part IV - Design and Construction, Bulletin 3, Diversion, Outlet, and Spillway Structures and Boulder Canyon Project, Final Report, Part I, 1946.

These reports presented the original design criteria for Hoover Dam (Boulder Dam). The total outlet capacity of Hoover Dam at the completion of construction was 520,000 ft^3/s. The spillways had a capacity of 400,000 ft^3/s; the outlet works could pass 100,000 $ft^3/$ s and the powerplant had a capacity of 20,000 ft^3/s.

4. The Colorado River and Its Proposed Development The Boulder Canyon Project, by Daniel W. Mead, March 11, 1929.

This report discusses the basin and its associated hydrology, as well as other facets of basin development. The advantages and disadvantages of the Boulder Canyon Project are discussed in some detail. The writer was unable to reach any definite conclusion as to whether or not the project is the best solution for the development of the lower Colorado River. He states that many of the water problems would be solved, but the project may never pay for itself.

1.5.2, Glen Canyon Dam

1. Cooperative Studies Report No. 9, Maximum Possible Flood Producing Meteorological Conditions: (1) Colorado River Basin above Glen Canyon Dam Site, (2) Colorado River Basin above Bridge Canyon Dam Site, (3) San Juan River above Bluff Dam Site, and (4) Little Colorado River above Coconino Dam Site, by the U.S. Weather Bureau, June 1949.

This study surveyed major storms which produced large rainfall depths over areas of 10,000 square miles or larger. A final estimate of the maximum possible rainfall and its seasonal variation in the Colorado River basin for the Glen Canyon, Bridge Canyon, Bluff, and Coconino dam sites was presented. The Bridge Canyon Dam site is located on the Colorado River between Glen Canyon and Hoover Dams.

Isohyetal maps were constructed for 42 storms. Storms were adjusted a maximum possible moisture condition for estimating the maximum possible storm. Another adjustment accounted for the rate of moist air inflow. Storms were not transposed from areas outside the basin. The time interval between major storms and types of storms were evaluated in a spaciotemporal manner.

The probable maximum snowpack was determined by the synthetic season method. The extent of snow cover was based on that which existed as the latest occurrence of the first five consecutive days above 32°F. The April 16th snowpack configuration was adopted as the probable maximum condition. Snow melt runoff factors were established by comparing historic runoff records with the total volume of the snowpack for several subbasins.

2. Spillway Design Flood Studies (Preliminary to Glen Canyon) - Bridge Canyon, Colorado River Storage (Glen Canyon Unit), and Coconino Projects, December 6, 1951, by W. R. Slater, Region 3.

Design flood studies were performed to estimate the probable maximum floods for Glen Canyon, Coconino, and Bridge Canyon dam sites. Table 1.5 shows the estimated design floods for each of these dams.

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Table 1.5.--1951 design floods for Glen Canyon, Coconino, and Bridge Canyon dam sites

Site	Drainage area (sq. mi.)	Peak (ft^3/s)	Volume (acre-feet)	Duration
Probable maximum Rain Floods:				
Glen Canyon	108,000	417,000	2,063,600	6 days
Coconino	26,200	566,000	1,260,100	6 days
Bridge Canyon	145,700	552,000	3,002,400	6 days
Probable Maximum Snowmelt Floods:				
Glen Canyon	108,000	196,100	28,460,200	Apr-July
Coconino	26,200	----	----	---
Bridge Canyon	145,700	196,900	26,832,600	Apr-July
Probable Maximum Spring Floods (snowmelt plus rain):				
Glen Canyon	108,000	196,100	28,923,900	Apr-July
Coconino	26,200	----	-----	---
Bridge Canyon	145,700	196,900	27,304,800	Apr-July

The peak and volume of the probable maximum rain flood were recommended for use as were the maximum volumes for the probable maximum snowmelt and spring floods. However, the peaks for the latter two floods were not adopted, since they were lower than the peak discharges experienced with the 1884 and 1921 floods. The study recommended revising the peak discharge estimates.

3. Inflow Design Flood Study, Glen Canyon Dam Site, Colorado River above Lees Ferry, Arizona, June 1954, by A.M. Gering.

This 1954 investigation revised the 1951 studies, but built upon many of the results. The snowmelt flood volume of 28,500,000 acre feet developed in the 1951 study was retained. The drainage basin above Glen Canyon was divided into the Green River, the Colorado River, and the San Juan River basins. Correlations between accumulated April-July runoff and accumulated maximum temperatures were used to shape the snow flood hydrograph. The volume was prorated to develop hydrographs for each basin. The hydrographs were added together and combined with a spring-type rain flood. The inflow design floods that were recommended for use in the design of the Glen Canyon Dam spillways are shown in table 1.6 and on figure 1.3.

Table 1.6.-- 1954 Glen Canyon inflow design flood

Flood Event	Peak (ft^3/s)	Volume (acre-feet)	Duration
Snowmelt + Rain	380,000	29,060,000	Apr-July
Probable Max Rain	417,000	2,063,600	6 days

Historic snowmelt season runoff was analyzed on a probability of occurrence basis to evaluate the diversion requirement flows for construction of Glen Canyon Dam. Diversion requirement hydrographs were developed, and the results are presented on table 1.7.

4. Review of Inflow Design Flood Study - Glen Canyon Dam Site - Colorado River Storage Project, April 5, 1955, by D. L. Miller.

The design floods developed in the June 1954 study were approved for use, as were the diversion requirement flood hydrographs. Recommendations on routing the inflow design flood through Glen Canyon Dam and Reservoir were also made as part of the review.

The reservoir was assumed to be at the top of the conservation pool, elevation 3700 feet (26,000,000 acre-feet), during the onset of the probable maximum rain flood. For the snowmelt plus rain event, the reservoir was assumed to contain 22,500,000 acre-feet of storage (elevation 3685 feet). Operations were based on runoff forecasts and an integrated criteria for operating Colorado River basin reservoirs.

Table 1.7.-- 1954 flood frequency analysis for Glen Canyon Dam

Frequency (years)	Peak discharge (ft^3/s)	Maximum volume 15-day (acre-feet)	Maximum volume 30-day (acre-feet)
5	118,000	2,723,800	4,936,100
10	150,000	3,180,000	5,600,000
25	196,000	3,550,000	6,400,000
50	238,000	3,880,000	7,000,000
100	284,600	4,265,200	7,614,600

5. Frequency Study, August through October Flows - Colorado River at Lees Ferry - Colorado River Storage Project, December 15, 1961, by Orville B. Ridgely.

A frequency study of non-snowmelt season discharges was completed. The study was performed using maximum 1-, 5-, 10-, 15-, and 20-day discharges at Lees Ferry. It was based on August through October flows for the 1921 through 1960 period. The analyses were used to supplement the results for the snowmelt season found in the 1954 study. The results are shown in table 1.8.

Table 1.8.--1961 flood frequency analysis for Glen Canyon Dam

Frequency (year)	Peak (ft^3/s)	Maximum Volume (acre-feet) 1-day	5-day	10-day	15-day	20-day
5	38,800	76,000	293,000	517,000	702,000	848,000
10	56,900	108,000	414,000	698,000	933,000	1,108,000
25	81,700	157,000	603,000	960,000	1,250,000	1,465,000

2.0 METEOROLOGICAL ANALYSIS

2.1 INTRODUCTION

The following is a summary of the procedure used to derive the ULDRS (Upper Limit Design Rainstorm) for the drainage above Hoover Dam in the Colorado River Basin. Details concerning this derivation are fully addressed in a report prepared for Reclamation by MKE. That report, titled "Hydrologic Design Data Acquisition - Determination of an Upper Limit Design Rainstorm for the Colorado River above Hoover Dam", was completed in March, 1989. The report developed two separate ULDRS's - one critical for inflow to Glen Canyon Dam and the other critical for inflow to Hoover Dam. Specific storm analyses involved determination of the ULDRS magnitude, spatial and temporal distributions, storm sequencing, and seasonal variation. In addition to the development of these criteria for the two individual ULDRS's determined from the contracted report, a third ULDRS was analyzed for another location in the drainage above Glen Canyon Dam. This ULDRS and associated data were developed by hydrometeorologists in Reclamation's Flood Section. Development of this third ULDRS was consistent with the agreed upon design scenarios that would be used for the determination of the critical design flood for Hoover Dam.

2.2 DATA COLLECTION

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 area of the subject drainage and the availability of extreme precipitation estimates from Hydrometeorological Report No. 49 for areas less than 5000 square miles, the search for critical storm data concentrated on finding severe rainfall events for areas greater than 5,000 square miles. A general literature search was performed. The purpose was to find all pertinent investigations which could be useful for the present analysis. This information, along with severe storm data maintained in the files of the Hydrometeorological Branch of the National Weather Service (NWS) and in the files of the Flood Section of Reclamation's Denver Office, served as a basis for identifying major storms of record. From a review of these data, 20 storms (table 2.1) were selected for detailed meteorological analyses and used to determine the causes of large-area heavy rainfall in the region.

In defining the ULDRS, determination of maximum average areal rainfall for major storms of record occurring in the basin and major storms of record considered transposable to the basin is required. Of the twenty storms for which detailed meteorological investigations were performed, thirteen storms (identified in table 2.1 with an asterisk) were analyzed to provide the necessary Depth-Area-Duration (DAD) data. Individual storm analyses used standard DAD procedures and a computer program developed by USBR to expedite the data processing.

Table 2.1.--Storms critical for the development of ULDRS over the Colorado River basin above Hoover Dam

Storm dates	Storm type[1]	General storm location	DAD available
October 4-6, 1911	T	AZ, CO, NM	Yes
April 5-9, 1926	ET	AZ, UT	No
September 11-13, 1927	T	AZ, CO, NM, UT	Yes
October 11-14, 1928	ET	UT	No
September 3-7, 1939	T	AZ, CO, UT	Yes
September 8-13, 1939	T	AZ, CO, NM, UT	Yes
May 30 - June 3, 1943	ET	CO, UT	Yes
October 26-29, 1946	ET	NV, UT	No
October 10-15, 1947	ET	AZ, CO, NM, UT	Yes
August 26-30, 1951	T	AZ, NV, UT	Yes
September 4-7, 1970	T	AZ, CO, UT	Yes
May 4-8, 1971	ET	NV, UT	No
September 28 - Oct. 2, 1971	T	AZ	No
October 3-7, 1972	T	AZ, CO	Yes
October 17-21, 1972	ET	AZ, NM	Yes
September 7-12, 1980	ET	UT	Yes
July 16-18, 1981	ET	CO, UT	No
September 26-Oct. 1, 1982	T	AZ, NM, UT	Yes
September 28-Oct. 2, 1983	T	AZ	No
July 20-23, 1984	ET	NV, UT	Yes

[1] T (Tropical Cyclone), ET (Extra-Tropical Cyclone)

2.3 DESIGN RAINSTORM SCENARIO

From the examination of the twenty selected storms, two hypothetical weather situations were developed that could cause the ULDRS over the study basin. One scenario involves a tropical cyclone developing over the tropical eastern Pacific Ocean to eventually penetrate the southwestern United States. Remnants of the tropical cyclone would then interact with mid-latitude upper-air circulation, which would enhance the rainfall potential of the storm. This Hypothetical-Upper Limit Design Rainstorm (HYPO-ULDRS) would occur sometime between late June and well into the fall season. The second HYPO-ULDRS scenario occurs from an optimum extra-tropical cyclone having abundant moisture inflow from the tropical Pacific. This type of major rainfall event could occur in either May or June and from mid September through October.

2.4 MAGNITUDE OF ULDRS

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 specific location of Glen Canyon Dam in relation to Hoover Dam. The objective was to provide the necessary design storms that would affect not only the design of Hoover, but also the design of Glen Canyon, or the two dams operating in combination. Examination of the isohyetal and isopercental (analysis of storm rainfall percentages of some rainfall index) patterns of rainfall associated with major storms occurring in the drainage were particularly useful in identifying three storm centerings at 370451 N, 1070451 W (San Juan Mountains); 38001 N, 1110401 W (Boulder Mountains); and 370151 N, 113*101 W (Pine and Cedar Mountains) and their related generic isohyetal patterns. Figure 2.1 indicates the location of the three storm centerings.

The ULDRS magnitude for each of the three storm centerings was evaluated by two separate approaches. Traditional techniques of design storm development were employed in developing each approach. However, both methodologies incorporated the use of a restriction to inflow moisture. This restriction to moisture availability was developed because the large areal extent of the drainage and corresponding design storms required evaluation. Differing from typical design storm studies, the full storm moisture maximization technique was restricted to the storm rainfall region of primary moisture inflow. Rainfall occurring beyond this region was adjusted by a reduced moisture maximization factor.

In developing the ULDRS magnitude, the first approach examined made use of techniques provided in NWS Hydrometeorological Report No. 55A. This approach is commonly referred to as the "storm separation" method whereby 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 procedure is based on: (1) estimating the convergence (nonorographic) portion of individual storm rainfall for key area sizes and durations, (2) moisture maximization and transposition of the convergence rainfall, (3) evaluating the adjusted convergence rainfall for orographic contributions, and (4) determining ULDRS values for a complete array of storm area sizes and durations.

The second approach made use of the traditional method of storm moisture maximization and transposition. In this procedure, individual storms were moisture maximized in place. A transposition index was selected to account for differences in storm precipitation due to orographic and distance from moisture source effects when individual storms were transposed from in situ centerings to selected design storm centerings. Transposed storm rainfall data were enveloped to complete an array of design storm areal and durational depths.

After evaluation of the assumptions and uncertainties involved in application of each approach, the results of each method were averaged to produce the final array of ULDRS depths. Table 2.2 provides the final averaged ULDRS precipitation values for each of the selected storm centerings.

2.5 SPATIAL AND TEMPORAL DISTRIBUTIONS OF ULDRS

Due to the large basin and storm areas involved, it was necessary to describe the spatial distribution of average areal ULDRS precipitation provided in table 2.2. This would permit the determination of average subbasin precipitation for any group of subbasins delineated within the total study region. To avoid the necessity of determining the spatial distribution of ULDRS precipitation for each of the area sizes indicated in table 2.2, hydrologic trials were conducted by Reclamation hydrologists using preliminary average areal precipitation. These results implied that, for an ULDRS type event, a storm area of 40,000 square miles was critical for development of the maximum inflow flood for both Hoover and Glen Canyon Dams. The ULDRS results for this area (table 2.2) were used in conjunction with DAD relations from major storms located in and surrounding the subject basin to develop ULDRS DAD curves. The ULDRS DAD relations and the 100-year, 24-hour precipitation-frequency maps that apportion regional rainfall were used to develop total storm and incremental isohyetal patterns for the three storm centerings. The total storm (72 hours) isohyetal maps for each selected centering are provided on figures 2.2 to 2.4.

Major storms in the region were examined to determine characteristic time distributions. Results from these investigations indicated a different temporal distribution would be appropriate for the storm centering located in the San Juan Mountains, compared to that found at the Pine/Cedar Mountain location. The same temporal distribution indicated for the San Juan Mountain centering was adopted for the Boulder Mountain centering. Figure 2.5 provides the temporal distributions for the ULDRS centerings used in this study.

2.6 STORM SEQUENCES

It was hypothesized that critical inflow to the dams could result from a series of storms occurring in sequence. Investigations were undertaken to define the relation between storm magnitude and dryperiod interval separating sequenced storms. Due to differences in storm types controlling the ULDRS on a seasonal basis, relations developed were separated into distinct spring and late summer/early fall categories. Pairs of storms that provided major rainfalls in and near the study region were examined for each defined season. Days separation between storms and the relation of the magnitude of areal rainfall both prior and subsequent to the main storm were noted. The resulting relations developed for each season were combined and are presented in figure 2.6. The relationships provided in this figure are only applicable for the sequenced events having individual storms centered on the San Juan, Boulder, or Pine/Cedar Mountains and having storm area sizes 40,000 square miles or larger.

Dry-day interval as used here is defined as the number of days of no rain separating the end of the rainfall from the first storm event to the beginning of rainfall from the second storm. One or both sequenced storms are of ULDRS magnitude dependent on season and dryday interval chosen. The relationship of secondary storm rainfall to primary (ULDRS) is independent of ULDRS positioning in the sequence (i.e., secondary storm rainfall can be placed either prior or after the ULDRS event).

2.7 SEASONAL VARIATION

Major floods in the study basin can occur as the result of melt of the snowpack that accumulated over the cool season from September through May. To assess adequately the flood potential for Hoover and Glen Canyon Dams, 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 and Glen Canyon Dams would likely result from the combination of the ULDRS event with the snowmelt hydrograph.

The evaluation of the ULDRS seasonal variation involved the use of both indirect (moisture/wind) as well as direct measures of precipitation. The examination revealed that 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 1, the seasonal variation of the ULDRS would indicate a decrease in rainfall potential. A greater decrease is indicated for the storm centering located in the drainage between Hoover and Glen Canyon Dams than that shown for the two storm centerings located above Glen Canyon Dam. Figure 2.7 indicates the adopted seasonal variation for the three centerings investigated in this study.

.3.0 HYDROLOGIC ANALYSIS

3.1 BASIN FIELD TRIPS

Prior to planning a field trip to the Colorado River basin, previous Reclamation flood studies were reviewed for other dams in the basin and for similar basins, such as Roosevelt Dam in

Arizona. Twenty seven studies were reviewed, and a compilation of lag-equation coefficients and loss rates was made. All of the recent studies were in the mountainous areas above Glen Canyon Dam. The areas which lacked hydrologic information and recent field investigations were the lower elevation, desert and foothill areas, plus nearly all of the Little Colorado River basin in northern Arizona. The field trips concentrated on collecting information in these areas, while relying on data from past studies for the necessary hydrologic parameters in the upper reaches of the basin.

Field trips were made through the lower basin (Hoover Dam to Glen Canyon Dam) and the upper basin (above Glen Canyon Dam) in June, 1987. Personnel from the Lower Colorado Regional Office and Denver office performed a reconnaissance of the lower part of the basin on June 1-3, 1987. They visited areas adjacent to Lake Mead (north and south sides), Muddy Creek, Meadow Valley Wash, Santa Clara River, Virgin River, Kanab Creek, Kaibab Creek, northern tributaries to the Little Colorado River, Zuni River, and the Little Colorado River. Personnel from the Upper Colorado Regional Office and Denver Office performed a reconnaissance of portions of the upper and lower basin, June 1-10, 1987. They visited the areas tributary to Lake Powell including the Paria River, Escalante River, Fremont River, Dirty Devil River, San Rafael River, lower Green River, and San Juan River.

The field trips were made to become familiar with the subbasins; to observe soil and geologic conditions for use in estimating loss or infiltration rates; to observe land use, vegetation type and cover, and basin roughness and steepness; and to observe evidence of previous high flows. Estimates of lag coefficients ("C" values) and loss rates, for use in deriving the probable maximum floods, were made for all of the subbasins visited.

In general, the lower basin near Lake Mead and the northside tributaries to Lake Mead are areas of low infiltration rates 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. (Loss rates are a measure of the precipitation lost to infiltration evaporation, transpiration, and absorption, and also to minor detention storage in the basin.) 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. Many of the loss rates used in the 1951 study were found to still be appropriate, although adjustments were necessary for some subbasins.

3.2 SUBBASIN DELINEATION

The Colorado River basin above Hoover Dam includes some 167,000 square miles. Of this total, 59,000 square miles are between Hoover Dam and Glen Canyon Dam in the lower basin, and 108,000 square miles are above Glen Canyon Dam in the upper basin. The lower and upper basins were divided into smaller subbasins for ease in meteorologic and hydrologic analysis. In general, subbasin delineation was made by following major tributary basin boundaries. Subbasins that had similar characteristics of elevation, slope, and stream development were combined where' possible. The size of the subbasins was limited to areas of less than 5,000 square miles. The lower basin was divided into 34 subbasins and the upper basin into 65 subbasins. The average subbasin size was about 1,700 square miles. Figure 3.1 shows the subbasin boundaries along with their identification numbers.

The base maps used for subbasin delineation were the "hydrologic unit" maps prepared by the

Geological Survey for the six states. These maps were published at a scale of 1:500,000. The maps provided a consistent set of basin boundaries for both the meteorologic and hydrologic studies. For the hydrologic investigation, subbasins were delineated from the river basin boundaries outlined on these maps. Some additional boundaries were established to divide basins at dam site locations, and some small basins were combined to facilitate computer modeling. Basin identification numbers were abbreviated from the hydrologic unit numbers supplied by the USGS.

3.3 BASIN PARAMETERS

The basin parameters of channel length, slope, and distance to the centroid were used in calculating basin factors and lag times. The stream length (L) was measured along the longest stream course from the basin outlet to the watershed divide. The basin centroid (Lca) was measured from the basin outlet to a point on the stream nearest the centroid. The subbasin's low elevation and high elevation along the longest stream course were used in calculating the stream slope (S). The basin factor (BF) was determined using the formula,

$$BF = \left(\frac{LLca}{S^{0.5}}\right)^{0.33}$$

These parameters are summarized in table 3.1 along with the drainage areas of each subbasin.

3.4 LOSS RATES

As previously stated, loss rates are a measure of the precipitation lost to infiltration, evaporation, transpiration, and absorption, and also to minor detention storage in the basin. Data to define or represent loss rates during an extreme event, such as a PMF, are very limited. Therefore, loss rates were estimated using previous studies and based on information gathered during the June 1987 field trips through the basin.

The loss rates used in previous inflow design and/or probable maximum flood studies were compiled and compared. The 1951 study included a substantial amount of information about loss rates. In that study, soil characteristics, surface geology, and vegetative cover were analyzed to estimate loss rates. Generalized surface geology and vegetative maps were prepared for the upper basin and portions of the lower basin. The area in the lower basin below the Bridge Canyon dam site was not included in the 1951 study because the original spillway studies for Hoover Dam did not use precipitation and/or loss rate data to develop the spillway design peaks and volumes. Examination of other flood studies also indicated a lack of loss rate information for much of the lower basin, especially in the desert area around Lake Mead.

In general, the lower basin areas adjacent to Lake Mead and the northside tributaries to Lake Mead were found to be areas of low loss rates and subject to flash flooding. The other tributary areas, especially Kanab Creek, Kaibab Creek, and most of the Little Colorado River basin, have somewhat higher loss rates. In general, the vegetative cover and loss rates 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 with sparse vegetation, and exhibited signs of flash flooding. The loss rates were quite low. Some portions of the lower Green River subbasin have extensive outcrops of Mancos Shale. The upper basin also exhibited the same increase in vegetation and loss rates with elevation increase as the lower basin.

Table 3.2 summarizes the field trip observations and relationships between elevation, vegetation, and soils, and the accompanying generalized estimates of "C" values and loss rates. This table represents a refinement of the application of the generalized criteria presented in table 3.3.

For this study, the delineated subbasins were further divided into the elevation bands shown on table 3.2. Weighted averages, based on the amount of area contained in each elevation band, were used to determine loss rates and "C" values for each subbasin. The results of this analysis are presented in table 3.1.

Many of the loss rates used in the 1951 study were found to still be appropriate, although adjustments were made for some subbasins. Table 3.4 is a comparison of the loss rates from the 1951 study with estimates based on observations made in 1987 for areas in the lower basin.

Table 3.2.--Lag coefficients and loss rates in relation to elevation, vegetation, and soils

Elevation (feet)	Vegetation/soils	"C" value	Loss rate (in/hr)
Colorado River Subbasins Northwest of Lakes Mead and Powell:			
Below 5500	Steep walled Rocky Canyons Cottonwoods along Streams Scattered Pinon and Juniper	0.8	0.10
5500 - 7000	Predominate Flat Desert Plateaus, Sage and Grass on Hard Crusted Sandy Soils	1.8	0.15
7000 - 8000	Pinon-Juniper Forest Mild Slopes with Crusted Sandy Soils	2.2	0.15
Above 8000	Ponderosa Pine Forests Steeper Slopes with Crusted Sandy Soils	2.5	0.15
Little Colorado River Subbasins South and East of Lake Powell:			
Below 4000	Canyons and Rocky Cliffs Little Vegetation Very Steep, Very Hard	0.8	0.10
4000 - 5500	Plateaus and Flat Deserts Scattered Sage and Grass Thin Crusted Sandy Soil Flat Terrain, some Rock Formations	2.0	0.25
5500 - 7000	Pinyon-Juniper Forest Scattered Sage and Grass Thin Crusted Very Sandy Mild Slopes, Eroded Gullies	2.2	0.20
Above 7000	Pine Forest with a Fair Amount of Forest Litter over Sandy Soils	2.5	0.25

Table 3.3.--Generalized guidelines for estimating lag coefficients

Watershed condition	"C" value
Forests	2.5 - 3.5
Sage, grass	1.8 - 2.5
Rocky, canyon areas	0.5 - 1.8

Table 3.4.--Comparison of loss rates

Study Subbasin	Loss Rate (in/hr) 1951	 1987
Upper Grand Canyon	.23	.20 - .25
Zuni and Upper Little Colorado Rivers .	.23	.20
Puerco Wash	.16	.20
Jadito Wash, Pueblo Colorado Wash	.23	.20 - .25
Lower Little Colorado and Cedar Wash	.18 - .23	.20 - .25
Upper Grand Canyon	.23	.20
Kanab Creek	.18	.20
Havasu Creek and Lower Grand Canyon	.25	.25

Table 3.1 showed the selected loss rates for the upper and lower basins. Loss rates developed in previous studies were used if they were available for the subbasins. In the other subbasins, the loss rates were determined by using the elevation-vegetation-loss rate relationship.

The areas around Lake Mead and Lake Powell were generally those with the lower loss rates. Those subbasins showed evidence of flash flooding and also had extensive areas of "desert pavement" - a very hard-packed, nearly impervious soil. Many of these subbasins had extensive rock outcrops. The vegetation in these subbasins was very sparse or non-existent. The higher plateaus and mountains generally have higher loss rates.

Some subbasins in the upper basin, generally west and north of Lake Powell, also are areas of low loss rates. These areas are more desert-like and more prone to flash floods than had been anticipated prior to the June, 1987 field trip.

MISSING 3.5 AND 3.6 (PAGE 39 OF ORIGINAL DOCUMENT)

To determine travel times for each of the channel reaches in the Colorado River basin, knowledge obtained from similar basins and similar studies was applied. Flood flow velocities usually range between 8 and 12 ft/s; therefore, average streambed slopes and channel conveyance characteristics were used to estimate the flow velocities. Generally, the steeper portions of the upper basin had the highest velocities, and the flatter areas around Lake Powell and Lake Mead had the lower values. The channel lengths were divided by the flow velocities to obtain travel times for each reach. Table 3.5 shows the selected travel times for each subbasin.

3.7 DIMENSIONLESS GRAPHS

The dimensionless unit hydrograph is used with the FHAR computer program 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) Southwest Desert for the desert areas, (2) Buckhorn for the foothill areas, and (3) Uinta for the mountainous areas. Tables 3.6, 3.7, and 3.8 show the unitgraph ordinates for the three dimensionless graphs. These dimensionless graphs were derived from analysis of flood events for the Salt River in Arizona, Buckhorn Creek in Colorado, and the Uinta Mountains in Utah. They are considered appropriate for use in this study.

Table 3.5.--Channel routing times between subbasins

Subbasin to subbasin	Distance (miles)	Velocity (ft/sec)	Travel time (hours)
Above Glen Canyon Dam			
44102-44101	36.0	12	4.4
44101-44104	22.9	12	2.8
44104-44103	35.2	12	4.3
44103-44106	0.7	12	0.1
44108-44107	54.8	12	6.7
44106-46001	60.5	12	7.4
44109-46001	18.8	12	2.3
45004-45003	66.3	12	8.1
45001-45003	72.8	12	8.9
45003-46001	42.5	12	5.2
46002-46001	48.3	12	5.9
46004-46003	50.7	12	6.2
46003-45007	1.5	11	0.2
45005-45007	100.6	12	12.3
45007-46006	6.0	11	0.8
46006-46005	96.0	11	12.8
46005-46009	39.5	10	5.8
46008-43005	90.8	9	14.8
41071-41062	32.7	12	4.0
41082-41072	19.6	12	2.4
41072-41062	13.9	12	1.7
41062-41003	58.9	12	7.2
41003-41004	18.0	12	2.2
42001-42003	12.3	12	1.5
42003-42072	3.3	12	0.4
42062-42004	33.5	12	4.1
42004-42006	16.4	12	2.0
42006-41005	48.3	12	5.9
41004-41006	56.5	12	6.9

41006-42005	32.7	12	4.0
42005-43001	35.3	11	4.7
43003-43005	58.5	11	7.8

Table 3.5.--Channel routing times between subbasins (continued)

Subbasin to subbasin	Distance (miles)	Velocity (ft/sec)	Travel time (hours)
Above Glen Canyon Dam			
41005-43005	30.0	11	4.0
43001-46008	92.0	10	13.5
47003-47001	57.1	9	9.3
43005-47001	16.7	7	3.5
48171-48103	17.2	12	2.1
48103-48105	23.7	12	2.9
48161-48106	27.8	12	3.4
48106-48201	29.5	12	3.6
48105-48202	25.2	10	3.7
48202-48203	9.5	10	1.4
48203-48205	25.2	10	3.7
48201-47001	70.0	9	11.4
Between Glen Canyon and Hoover Dams			
52001-52003	21.3	12	2.6
52003-52004	16.4	12	2.0
52004-52005	26.2	12	3.2
52005-52008	13.1	12	1.6
52006-52008	64.6	12	7.9
52007-52009	4.9	12	0.6
52013-52014	4.9	12	0.6
52014-52008	8.2	12	1.0
52007-52009	4.9	12	0.6
52009-52010	21.3	12	2.6
52010-52011	9.8	12	1.2
52011-52012	36.0	12	4.4
52012-52015	4.9	12	0.6
52015-52016	20.5	12	2.5
52008-52017	4.1	12	0.5
52017-52018	36.0	12	4.4
52018-51001	48.3	12	5.9
47007-52016	58.9	12	7.2
52016-51002	26.2	12	3.2
51001-51003	55.2	10	8.1
51003-51004	13.0	10	1.9
51004-51005	80.5	10	11.8
51009-51005	58.6	10	8.6
51011-51013	51.5	12	6.3
51013-51005	13.1	12	1.6
51002-51005	4.1	1	6.0

Table 3.6.--Southwest desert dimensionless hydrograph

Southwest Desert Great Basin and Colorado Plateau
(Reclamation Flood Hydrology Manual Table 4-13, 1989)

% Lag+D/2	Flow (ft ^{3}/s)	% Lag+D/2	Flow (ft ^{3}/s)	% Lag+D/2	Flow (ft ^{3}/s)	% Lag+D/2	Flow (ft ^{3}/s)
0	0.00	135	9.04	270	1.68	405	0.38
5	0.19	140	8.20	275	1.59	410	0.36
10	0.32	145	7.36	280	1.50	415	0.34
15	0.48	150	6.78	285	1.43	420	0.33
20	0.74	155	6.20	290	1.36	425	0.30
25	1.21	160	5.83	295	1.28	430	0.28
30	1.81	165	5.47	300	1.21	435	0.27
35	2.63	170	5.15	305	1.15	440	0.26
40	3.68	175	4.84	310	1.08	445	0.24
45	5.47	180	4.57	315	1.02	450	0.23
50	8.41	185	4.31	320	0.97	455,	0.22
55	12.61	190	4.10	325	0.91	460	0.21
60	16.50	195	3.87	330	0.86	465	0.20
65	20.50	200	3.68	335	0.82	470	0.19
70	23.97	205	3.47	340	0.78	475	0.18
75	27.75	210	3.28	345	0.74	480	0.17
80	28.91	215	3.10	350	0.69	485	0.16
85	28.07	220	2.93	355	0.66	490	0.15
90	26.38	225	2.75	360	0.63	495	0.15
95	24.18	230	2.63	365	0.59	500	0.13
100	21.55	235	2.47	370	0.56	505	0.12
105	18.92	240	2.33	375	0.53	510	0.12
110	16.08	245	2.22	380	0.50	515	0.11
115	14.19	250	2.10	385	0.47	520	0.10
120	12.61	255	1.99	390	0.45		
125	11.04	260	1.88	395	0.42		
130	9.99	265	1.78	400	0.40		

Table 3.7.--Buckhorn dimensionless hydrograph

Rocky Mountain Thunderstorm
(Reclamation Flood Hydrology manual Table 4-11, 1989)

% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)
0	0.00'	155	5.98	310	1.00	465	0.26
5	0.14	160	5.47	315	0.96	470	0.25
10	0.21	165	4.97	320	0.92	475	0.24
15	0.33	170	4.55	325	0.88	480	0.23
20	0.51	175	4.25	330	0.84	485	0.22
25	0.84	180	3.89	335	0.81	490	0.21
30	1.62	185	3.59	340	0.77	495	0.20
35	3.74	190	3.34	345	0.74	500	0.19
40	6.38	195	3.13	350	0.71	505	0.18
45	8.61	200	2.93	355	0.68	510	0.17
50	10.94	205	2.75	360	0.65	515	0.17
55	13.26	210	2.61	365	0.62	520'	0.16
60	15.70	215	2.44	370	0.59	525	0.16
65	18.23	220	2.31	375	0.57	530	0.15
70	20.76	225	2.17	380	0.55	535	0.15
75	23.30	230	2.04	385	0.52	540	0.14
80	25.83	235	1.95	390	0.50	545	0.14
85	28.36	240	1.84	395	0.48	550	0.13
90	26.53	245	1.76	400	0.46	555	0.13
95	24.71	250	1.69	405	0.43	560	0.12
100	22.68	255	1.62	410	0.42	565	0.12
105	20.76	260	1.55	415	0.40	570	0.11
110	18.84	265	1.49	420	0.38	575	0.11
115	16.81	270	1.42	425	0.36	580	0.10
120	14.99	275	1.36	430	0.35	585	0.10
125	12.86	280	1.30	435	0.33	590	0.09
130	11.04	285	1.24	440	0.32	595	0.09
135	9.52	290	1.19	445	0.31	600	0.08
140	8.41	295	1.14	450	0.29		
145	7.50	300	1.09	455	0.28		
150	6.69	305	1.05	460	0.27		

Table 3.8.--Uinta dimensionless hydrograph

Rocky Mountain General Storm
(Reclamation Flood Hydrology manual Table 4-9, 1989)

% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)	% Lag+D/2	Flow (ft^3/s)
0	0.00	155	6.40	310	1.57	465	0.44
5	0.26	160	6.00	315	1.50	470	0.42
10	0.90	165	5.65	320	1.45	475	0.41
15	2.00	170	5.35	325	1.39	480	0.40
20	3.00	175	5.00	330	1.34	485	0.38
25	5.00	180	4.80	335	1.28	490	0.37
30	6.80	185	4.55	340	1.23	495	0.35
35	7.70	190	4.30	345	1.19	500	0.34
40	9.00	195	4.10	350	1.13	505	0.33
45	14.51	200	3.90	355	1.09	510	0.32
50	18.11	205	3.72	360	1.05	515,	0.29
55	21.51	210	3.55	365	1.01	520	0.28
60	24.01	215	3.40	370	0.97	525	0.27
65	22.81	220	3.25	375	0.93	530	0.26
70	21.21	225	3.10	380	0.90	535	0.25
75	19.31	230	3.00	385	0.86	540	0.24
80	16.91	235	2.87	390	0.83	545	0.23
85	15.21	240	2.75	395	0.80	550	0.23
90	14.21	245	2.65	400	0.77	555	0.22
95	13.41	250	2.52	405	0.74	560	0.21
100	12.71	255	2.42	410	0.68	565	0.20
105	11.91	260	2.33	415	0.65	570	0.19
110	11.21	265	2.24	420	0.63	575	0.19
115	10.61	270	2.15	425	0.60	580	0.18
120	10.01	275	2.07	430	0.58	585	0.17
125	9.40	280	1.99	435	0.56	590	0.17
130	8.80	285	1.91	440	0.54	595	0.16
135	8.25	290	1.83	445	0.52	600	0.16
140	7.70	295	1.76	450	0.50		
145	7.25	300	1.70	455	0.48		
150	6.80	305	1.63	460	0.46		

4.0 ANTECEDENT FLOOD ANALYSIS

4.1 GENERAL

The antecedent flood is that flood, and associated climatic conditions, affecting the basin prior to the onset of the Upper Limit Design Rain Storm (ULDRS). 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.

4.2 METHODOLOGY FOR DEVELOPING THE ANTECEDENT FLOODS

A statistical analysis of flood flows for the Colorado River above Hoover Dam was the basis for developing the snowmelt base flood. Flooding in the Colorado River Basin is dominated by snowmelt runoff. The basic data were not adjusted to remove the effects of rainfall runoff. The assumption was made that the data include rainfall similar to that which would be found in any year in which the ULDRS might occur. The 100-year flood volume was determined for various time intervals, up to and including a full year period. This information was used to construct an annual daily flow hydrograph that is hydrologically reasonable. The 100-year flood volumes for the area above Glen Canyon Dam and between Glen Canyon Dam and Hoover Dam were also calculated in the same manner as the 100-year inflow to Hoover Dam.

The timing of the peak of the hydrograph was based on observations of time of occurrence of flood peaks during the years of record. The shape of the daily flows near the peak of the hydrograph could not be based on the monthly data base itself, and accordingly was patterned after the 1984 flood hydrograph. Runoff in 1984 resulted in a single peaked hydrograph of the same order of magnitude as the 100-year snowmelt flood.

To accommodate the modeling requirements for the flood control and storage operations of the upstream storage facilities, the inflow hydrograph was separated into two constituent hydrographs, one for inflow into Glen Canyon Dam and one for the intervening area between Glen Canyon Dam and Hoover Dam. A 100-year balanced hydrograph was calculated for the flows into Glen Canyon Dam, and the remainder of the flow was the concurrent intervening inflow (i.e., the difference between the Hoover Dam 100-year inflow and the Glen Canyon Dam 100-year inflow).

The data used for statistical analysis were the undepleted, unregulated, natural flow data base that was prepared for use with the Colorado River Simulation System (CRSS). These data consist of monthly flows for the period from 1906 to 1983. The data base was augmented by provisional values for 1984 to 1986.Both log-Pearson type III and Pearson type III frequency analyses were performed, and the Pearson type III was found to be more applicable. This decision was based on both theoretical considerations and results of analyses of the data. The-frequency analysis was performed for volumes with durations of one month, two months, etc. An adjustment was made to the results to arrive at 100-year peak 30-day volumes, 60-day volumes, etc. based on the 100-year peak one monthly volume, two monthly volumes, etc. This adjustment, used to compensate for the fixed interval of the base data, was very small. It was less than 6 percent for 30 days and practically negligible for periods longer than 60 days. An inspection of the data shows that the adjustment was not dependent on the magnitude of runoff. These flood frequency curves are illustrated on figures 4.1 and 4.2 for Lakes Powell and Mead, respectively.

The resulting 100-year volumes were used with the balanced hydrograph procedure to arrive at daily hydrograph values. The values near the peak, those for the peak thirty days, were patterned to resemble the shape of the peak experienced during the natural runoff into Glen Canyon Dam in 1984. The remainder of the hydrograph was patterned to reflect a shape typical of that normally experienced in high runoff years. The timing within the year was also determined based on that normally experienced in high runoff years.

The 100-year peak volumes were examined for temporal consistency. The values for the 90-day peak volume appeared excessively large with respect to all of the other values. Therefore, in order to arrive at a reasonably consistent hydrograph, the 90-day values were adjusted downward. This adjustment amounts to 2 percent for the inflow into Hoover Dam. The intervening flows are approximately 5 percent or less of the total and were also smoothed temporally for consistency. It should be noted that as a computational expediency the peak 10, 11, and 12 month volumes were calculated using water year data, but these values were used in constructing a hydrograph for the calendar year. This discrepancy is insignificant in terms of this study.

4.3 ANTECEDENT FLOODS FOR HOOVER AND GLEN CANYON

The resulting ordinates of the 100-year hydrograph for inflow into Hoover Dam are shown in table 4.1. Table 4.2 provides the ordinates for the 100-year inflow hydrograph for Glen Canyon Dam, and table 4.3 lists the concurrent flow in the intervening reach between Hoover and Glen Canyon Dams. The ordinates from tables 4.2 and 4.3 for any given day sum to give the corresponding unregulated, undepleted daily flow in table 4.1.

Table 4.4 summarizes the results of the separation technique used in the snowmelt flood analysis. The method calculated a 100-year balanced snowmelt hydrograph for flows into Glen Canyon, with the remainder of the 100-year inflow to Hoover Dam coming from the intervening area between the dams.

Table 4.1.--Undepleted unregulated 100-year base snowmelt - Hoover Dam

Daily inflow to Hoover Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
0	0	50	11,203	100	26,286	150	166,433
1	10,910	51	10,799	101	26,887	151	161,271
2	10,990	52	10,401	102	27,925	152	156,103
3	11,066	53	9,997	103	28,964	153	152,115
4	11,147	54	9,670	104	30,002	154	148,117
5	11,227	55	9,352	105	31,036	155	144,119
6	11,303	56	8,808	106	32,075	156	140,126
7	11,383	57	8,349	107	33,113	157	137,050
8	11,459	58	7,643	108	34,147	158	133,980
9	11,540	59	7,290	1.09	35,191	159	130,905
10	11,620	60	7,890	110	36,224	160	127,834
11	11,696	61	8,485	ill	37,267	161	124,764
12	11,777	62	9,085	112	38,886	162	121,683
13	11,852	63	9,831	113	41,931	163	118,613
14	11,933	64	11,480	114	45,047	164	115,543
15	12,014	65	12,614	115	48,157	165	110,270
16	12,089	66	13,093	116	50,265	166	107,401
17	12,170	67	13,562	117	51,363	167	104,533
18	12,246	68	14,041	118	52,463	168	101,669
19	12,326	69	14,515	119	53,557	169	98,800
20	12,407	70	14,994	120	54,661	170	95,936
21	12,483	71	15,493	121	55,760	171	93,310
22	12,563	72	16,652	122	56,859	172	92,115
23	12,664	73	18,080	123	57,958	173	91,162
24	12,881	74	18,947	124	59,053	174	90,204
25	13,118	75	19,259	125	60,156	175	89,246

26	13,355	76	19,571	126	61,255	176	88,294
27	13,592	77	19,879	127	62,969	177	87,341
28	13,824	78	20,186	128	66,201	178	86,383
29	14,061	79	20,504	129	69,498	179	85,425
30	14,297	80	20,812	130	72,791	180	84,472
31	14,349	81	21,124	131	77,545	181	83,514
32	14,213	82	21,432	132	83,750	182	82,561
33	14,081	83	21,744	133	89,962	183	81,608
34	13,945	84	22,138	134	102,390	184	80,650
35	13,814	85	22,990	135	115,543	185	79,692
36	13,678	86	23,918	136	127,834	186	78,734
37	13,547	87	24,855	137	140,126	187	77,787
38	13,416	88	25,349	138	156,103	188	76,829
39	13,279	89	25,399	139	158,977	189	75,871
40	13,012	91	25,506	141	164,709	191	72,791
42	12,881	92	25,561	142	167,578	192	69,498
43	12,746	93	25,616	143	170,441	193	66,201
44	12,609	94	25,672	144	173,315	194	62,969
45	12,478	95	25,722	145	176,184	195	61,255
46	12,342	96	25,777	146	179,047	196	60,156
47	12,211	97	25,833	147	181,916	197	59,053
48	11,999	98	25,965	148	176,754	198	57,958
49	11,605	99	26,126	149	171,596	199	56,859

Table 4.1.--Undepleted unregulated 100-year base snowmelt -Hoover Dam (continued)

Daily inflow to Hoover Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
200	55,760	242	22,632	284	9,660	326	8,858
201	54,661	243	22,007	285	9,503	327	8,909
202	53,557	244	21,739	286	9,357	328	8,959
203	52,463	245	21,482	287	9,216	329	9,014
204	51,363	246	21,225	288	9,075	330	9,059
205	50,265	247	20,963	289	8,929	331	9,120
206	48,157	248	20,711	290	8,787	332	9,170
207	45,047	249	20,453	291	8,641	333	9,226
208	41,931	250	20,196	292	8,495	334	9,281
209	38,886	251	19,944	293	8,354	335	9,337
210	37,267	252	19,687	294	8,213	336	9,388
211	36,224	253	19,430	295	8,066	337	9,428
212	35,191	254	19,179	296	7,925	338	9,443
213	34,147	255	18,922	297	7,779	339	9,463
214	33,113	256	18,503	298	7,633	340	9,478
215	32,075	257	17,918	299	7,497	341	9,499
216	31,036	258	17,333	300	7,350	342	9,514
217	30,002	259	16,748	301	7,204	343	9,539
218	28,964	260	16,168	302	7,058	344	9,554
219	27,925	261	15,634	303	7,063	345	9,569
220	26,887	262	15,392	304	7,215	346	9,589
221	26,312	263	15,195	305	7,366	347	9,605

222	26,196	264	15,004	306	7,517	348	9,625
223	26,080	265	14,807	307	7,673	349	9,645
224	25,960	266	14,615	308	7,825	350	9,665
225	25,853	267	14,419	309	7,970	351	9,680
226	25,803	268	14,222	310	8,051	352	9,695
227	25,767	269	14,031	311	8,102	353	9,716
228	25,727	270	13,834	312	8,152	354	9,730
229	25,687	271	13,643	313	8,198	355	9,755
230	25,652	272	13,446	314	8,253	356	9,770
231	25,611	273	13,249	315	8,304	357	9,790
232	25,571	274	13,058	316	8,349	358	9,790
233	25,536	275	12,861	317	8,405	359	9,790
234	25,491.	276	12,670	318	8,455	360	9,790
235	25,455	277	12,478	319	8,505	361	9,790
236	25,414	278	12,161	320	8,555	362	9,790
237	25,374	279	11,732	321	8,606	363	9,790
238	25,339	280	11,298	322	8,656	364	9,790
239	24,935	281	10,870	323	8,707	365	9,790
240	24,164	282	10,436	324	8,757		
241	23,398	283	10,008	325	8,808		

Table 4.2.--Undepleted unregulated 100-year base snowmelt - Glen Canyon Dam

Daily inflow to Glen Canyon Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
0	0	so	9,927	100	24,179	150	164,195
1	9,887	51	9,493	101	24,764	151	159,103
2	9,967	52	9,065	102	25,818	152	154,006
3	10,043	53	8,631	103	26,867	153	150,068
4	10,124	54	8,268	104	27,920	154	146,126
5	10,204	55	7,900	105	28,969	155	142,183
6	10,280	56	7,250	106	30,018	156	138,240
7	10,360	57	6,690	107	31,071	157	135,210
8	10,436	58	5,818	108	32,120	158	132,180
9	10,517	59	5,319	109	33,174	159	129,145
10	10,597	60	5,924	110	34,222	160	126,115
11	10,673	61	6,529	ill	35,276	161	123,085
12	10,754	62	7,134	112	36,915	162	120,050
13	10,829	63	7,890	113	40,000	163	117,020
14	10,910	64	9,554	114	43,156	164	113,990
15	10,991	65	10,698	115	46,307	165	108,737
16	11,066	66	11,167	116	48,425	166	105,803
17	11,147	67	11,631	117	49,498	167	102,874
18	11,223	68	12,100	118	50,577	168	99,945
19	11,303	69	12,569	119	51,651	169	97 , 015
20	11,384	70	13,038	120	52,730	170	94,086
21	11,460	71	13,532	121	53,809	171	91,399
22	11,540	72	14,671	122	54,883	172	90,179
23	11,636	73	16,078	123	55,962	173	89,206
24	11,853	74	16,935	124	57,036	174	88,228
25	12,090	75	17,257	125	58,114	175	87 , 250
26	12,327	76	17,575	126	59,193	176	86,272

27	12,564	77	17,893	127	60,872	177	85,299
28	12,796	78	18,210	128	64,038	178	84,321
29	13,033	79	18,533	129	67,270	179	83,343
30	13,269	80	18,851	130	70,497	180	82,370
31	13,315	81	19,168	131	75,286	181	81,391
32	13,169	82	19,486	132	81,633	182	80,413
33	13,027	83	19,808	133	87,981	183	79,440
34	12,881	84	20,207	134	100,681	184	78,462
35	12,740	85	21,084	135	113,990	185	77,484
36	12,594	86	22,037	136	126,115	186	76,506
37	12,448	87	22,995	137	138,240	187	75,533
38	12,307	88	23,494	138	154,006	188	74,555
39	12,160	89	23,534	139	156,839	189	73,577
40	12,019	90	23,569	140	159,667	190	72, 604
41	11,873	91	23,610	.141	162,496	191	70,497
42	11,732	92	23,650	142	165,324	192	67,270
43	11,586	93	23,690	143	168,152	193	64,038
44	11,439	94	23,731	144	170,986	194	60,872
45	11,298	95	23,766	145	173,814	195	59,193
46	11,152	96	23,806	146	176,642	196	58,114
47	11,011	97	23,847	147	179,471	197	57,036
48	10,784	98	23,943	148	174,379	198	55,962
49	10,360	99	24,064	149	169,287	199	54,883

Table 4.2.--Undepleted unregulated 100-year base snowmelt - Glen Canyon Dam (continued)

Daily inflow to Glen Canyon Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
200	53,809	242	20,716	284	7,714	326	7,315
201	52,730	243	20,076	285	7,557	327	7,376
202	51,651	244	19,798	286	7,411	328	7,436
203	50,577	245	19,536	287	7,265	329	7,502
204	49,498	246	19,274	288	7,124	330	7,562
205	48,425	247	19,007	289	6,978	331	7,628
206	46,307	248	18,745	290	6,831	332	7,688
207	43,156	249	18,482	291	6,685	333	7,754
208	40,000	250	18,220	292	6,539	334	7,814
209	36,915	251	17,958	293	6,393	335	7,880
210	35,276	252	17,696	294	6,252	336	7,941
211	34,222	253	17,434	295	6,105	337	7,986
212	33,174	254	17,172	296	5,959	338	8,006
213	32,120	255	16,910	297	5,813	339	8,026
214	31,071	256	16,491	298	5,667	340	8,046
215	30,018	257	15,916	299	5,526	341	8,067
216	28,969	258	15,342	300	5,379	342	8,087
217	27,920	259	14,767	301	5,233	343	8,112
218	26,867	260	14,197	302	5,087	344	8,132
219	25,818	261	13,668	303	5,107	345	8,152
220	24,764	262	13,431	304	5,294	346	8,172
221	24,200	263	13,239	305	5,480	347	8,193
222	24,114	264	13,048	306	5,667	348	8,213

223	24,028	265	12,856	307	5,853	349	8,238
224	23,943	266	12,664	308	6,040	350	8,258
225	23,862	267	12,473	309	6,221	351	8,278
226	23,827	268	12,281	310	6,322	352	8,298
227	23,801	269	12,090	311	6,383	353	8,319
228	23,771	270	11,898	312	6,443	354	8,339
229	23,741	271	11,707	313	6,504	355	8,364
230	23,716	272	11,515	314	6,569	356	8,384
231	23,685	273	11,323	315	6,630	357	8,404
232	23,655	274	11,132	316	6,690	358	8,404
233	23,630	275	10,940	317	6,756	35 9	8,404
234	23,600	276	10,754	318	6,816	360	8,404
235	23,574	277	10,562	319	6,877	361	8,404
236	23,544	278	10,245	320	6,942	362	8,404
237	23,514	279	9,811	321	7,003	363	8,404
238	23,489	280	9,372	322	7,063	364	8,404
239	23,080	281	8,939	323	7,129	365	8,404
240	22,289	282	8,500	324	7,189		
241	21,502	283	8,067	325	7,250		

Table 4.3.--Undepleted unregulated 100-year base snowmelt - intervening area between Hoover and Glen Canyon Dams

Glen Canyon Dam to Hoover Dam intervening daily inflow

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
0	0	50	1,276	100	2,107	150	2,238
1	1,023	51	1,306	101	2,123	151	2,168
2	1,023	52	1,336	102	2,107	152	2,097
3	1,023	53	1,366	103	2,097	153	2,047
4	1,023	54	1,402	104	2,082	154	1,991
5	1,023	55	1,452	105	2,067	155	1,936
6	1,023	56	1,558	106	2,057	156	1,886
7	1,023	57	1,659	107	2,042	157	1,840
8	1,023	58	1,825	108	2,027	158	1,800
9	1,023	59	1,971	109	2,017	159	1,760
10	1,023	60	1,966	110	2,002	160	1,719
11	1,023	61	1,956	ill	1,991	161	1,679
12	1,023	62	1,951	112	1,971	162	1,633
13	1,023	63	1,941	113	1,931	163	1,593
14	1,023	64	1,926	114	1,891	164	1,553
15	1,023	65	1,916	115	1,850	165	1,533
16	1,023	66	1,926	116	1,840	166	1,598
17	1,023	67	1,931	117	1,865	167	1,659
18	1,023	68	1,941	118	1,886	168	1,724
19	1,023	69	1,946	119	1,906	169	1,785
20	1,023	70	1,956	120	1,931	170	1,850
21	1,023	71	1,961	121	1,951	171	1,911
22	1,023	72	1,981	122	1,976	172	1,936
23	1,028	73	2,002	123	1,996	173	1,956
24	1,028	74	2,012	124	2,017	174	1,976

25	1,028	75	2,002	125	2,042	175	1,996
26	1,028	76	1,996	126	2,062	176	2,022
27	1,028	77	1,986	127	2,097	177	2,042
28	1,028	78	1,976	128	2,163	178	2,062
29	1,028	79	1,971	129	2,228	179	2,082
30	1,028	80	1,961	130	2,294	180	2,102
31	1,034	81	1,956	131	2,259	181	2,123
32	1,044	82	1,946	132	2,117	182	2,148
33	1,054	83	1,936	133	1,981	183	2,168
34	1,064	84	1,931	134	1,709	184	2,188
35	1,074	85	1,906	135	1,553	185	2,208
36	1,084	86	1,881	136	1,719	186	2,228
37	1,099	87	1,860	137	1,886	187	2,254
38	1,109	88	1,855	138	2,097	188	2,274
39	1,119	89	1,865	139	2,138	189	2,294
40	1,129	90	1,881	140	2,178	190	2,314
41	1,139	91	1,896	141	2,213	191	2,294
42	1,149	92	1,911	142	2,254	192	2,228
43	1,160	93	1,926	143	2,289	193	2,163
44	1,170	94	1,941	144	2,329	194	2,097
45	1,180	95	1,956	145	2,370	195	2,062
46	1,190	96	1,971	146	2,405	196	2,042
47	1,200	97	1,986	147	2,445	197	2,017
48	1,215	98	2,022	148	2,375	198	1,996
49	1,245	99	2,062	149	2,309	199	1,976

Table 4.3.--Undepleted unregulated 100-year base snowmelt - intervening area between Hoover and Glen Canyon Dams (continued)

Glen Canyon Dam to Hoover Dam intervening daily inflow

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
00	1,951	242	1,916	284	1,946	326	1,543
201	1,931	243	1,931	285	1,946	327	1,533
202	1,906	244	1,941	286	1,946	328	1,523
203	1,886	245	1,946	287	1,951	329	1,512
204	1,865	246	1,951	288	1,951	330	1,497
205	1,840	247	1,956	289	1,951	331	1,492
206	1,850	248	1,966	290	1,956	332	1,482
207	1,891	249	1,971	291	1,956	333	1,472
208	1,931	250	1,976	292	1,956	334	1,467
209	1,971	251	1,986	293	1,961	335	1,457
210	1,991	252	1,991	294	1,961	336	1,447
211	2,002	253	1,996	295	1,961	337	1,442
212	2,017	254	2,007	296	1,966	338	1,437
213	2,027	255	2,012	297	1,966	339	1,437
214	2,042	256	2,012	298	1,966	340	1,432
215	2,057	257	2,002	299	1,971	341	1,432
216	2,067	258	1,991	300	1,971	342	1,427
217	2,082	259	1,981	301	1,971	343	1,427
218	2,097	260	1,971	302	1,971	344	1,422
219	2,107	261	1,966	303	1,956	345	1,417

220	2,123	262	1,961	304	1,921	346	1,417
221	2,112	263	1,956	305	1,886	347	1,412
222	2,082	264	1,956	306	1,850	348	1,412
223	2,052	265	1,951	307	1,820	349	1,407
224	2,017	266	1,951	308	1,785	350	1,407
225	1,991	267	1,946	309	1,749	351	1,402
226	1,976	268	1,941	310	1,729	352	1,397
227	1,966	269	1,941	311	1,719	353	1,397
228	1,956	270	1,936	312	1,709	354	1,391
229	1,946	271	1,936	313	1,694	355	1,391
230	1,936	272	1,931	314	1,684	356	1,386
231	1,926	273	1,926	315	1,674	357	1,386
232	1,916	274	1,926	316	1,659	358	1,386
233	1,906	275	1,921	317	1,649	359	1,386
234	1,891	276	1,916	318	1,639	360	1,386
235	1,881	277	1,916	319	1,628	361	1,386
236	1,870	278	1,916	320	1,613	362	1,386
237	1,860	279	1,921	321	1,603	363	1,386
238	1,850	280	1,926	322	1,593	364	1,386
239	1,855	281	1,931	323	1,578	365	1,386
240	1,875	282	1,936	324	1,568		
241	1,896	283	1,941	325	1,558		

Table 4.4.--Summary of 100-year base snowmelt flood

	Volume (acre-feet)
Glen Canyon Dam Inflow	25,375,000
Intervening Inflow	1,281,000
Hoover Dam Inflow	26,656,000

4.4 MONTHLY INFLOWS TO MAJOR UPPER BASIN RESERVOIRS

Snowmelt inflows to other reservoirs in the upper basin were also developed. A simplified approach was chosen for distributing a portion of the inflows to Glen Canyon to the upstream reservoirs. Base snowmelt flows were calculated using a ratio of the average annual runoff at the upstream point to the average annual runoff at Glen Canyon using 1906-1986 CRSS data. Snowmelt inflow hydrographs were developed for Blue Mesa, Crystal, Fontenelle, Flaming Gorge, and Navajo Reservoirs.

Natural flow data were compiled from the CRSS data base for the 1906-1983 period and from provisional CRSS data for the 1984-1986 period. The average monthly flows at the stations of concern in the Colorado River basin along with the monthly flow distribution percentages are shown in table 4.5. Table 4.6 shows the ratio of the average annual flows at the reservoirs of concern to the flows at Glen Canyon Dam. The ratios were applied to the 100-year base snowmelt flood into Glen Canyon to obtain the base snowmelt flood at each reservoir.

A comparison of 1906-1986 monthly flow distributions versus the 1984 actual CRSS monthly flow data indicated good agreement. Therefore, the 1906-1986 monthly distributions were used to calculate the monthly 100-year base snowmelt flood flows for the stations upstream from Glen Canyon. The results are presented in tables 4.7 and 4.8.

Table 4.5.--Average monthly natural flows for 1906 through 1986 for major reservoirs in the upper basin

Reservoir inflow in acre-feet / monthly percentage

Month	Blue Mesa	Crystal	Fontenelle	Flaming Gorge	Navajo	Glen Canyon
Jan	23,000	28,000	28,000	34,000	19,000	337,000
	2.00	2.08	2.03	1.69	1.53	2.22
Feb	21,000	25,000	27,000	40,000	25,000	376,000
	1.82	1.86	1.95	1.99	2.02	2.48
Mar	33,000	41,000	49,000	96,000	71,000	641,000
	2.86	3.05	3.55	4.77	5.73	4.16
		1				
Apr	86,000	109,000	101,000	177,000	180,000	1,219,000
	7.47	8.10	7.31	8.80	14.53	8.04
May	251,000	306,000	209,000	347,000	303,000	3,142,000
	21.79	22.73	15.12	17.26	24.46	20.57
June	339,000	394,000	400,000	575,000	298,000	4,250,000
	29.43	29.27	28.94	28.59	24.05	27.63
July	164,000	181,000	266,000	360,000	124,000	2,238,000
	14.24	13.44	19.25	17.90	10.01	14.54
Aug	87,000	94,000	121,000	154,000	67,000	1,079,000
	7.55	7.00	8.76	7.66	5.41	7.04
Sept	48,000	53,000	61,000	77,000	54,000	656,000
	4.17	3.93	4.41	3.83	4.36	4.22
Oct	41,000	47,000	60,000	64,000	49,000	574,000
	3.55	3.49	3.62	3.18	3.95	3.72
Nov	33,000	38,000	39,000	52,000	29,000	460,000
	2.86	2.82	2.82	2.59	2.34	3.00
Dec	26,000	30,000	31,000	35,000	20,000	360,000
	2.26	2.23	2.24	1.74	1.61	2.38
Total	1,152,000	1,346,000	1,382,000	2,011,000	1,239,000	'15,332,000

Table 4.6 -- [?] reservoirs in the upper basin

Reservoir	Ratio of average annual flow to avg. annual flow at Glen Canyon (%)	Annual base snowmelt flood volume (acre-feet)
Blue Mesa	7.51	1,906,600
Crystal	8.78	2,227,700
Fontenelle	9.01	2,287,300
Flaming Gorge	13.12	3,328,300
Navajo	8.08	2,050,600

Table 4.7.--100-year base snowmelt floods for Blue Mesa, Crystal, and Fontenelle reservoirs

Month	100-year base snowmelt floods Blue Mesa (acre-feet)	Crystal (acre-feet)	Fontenelle (acre-feet)
January	38,100	46,300	46,400
February	34,700	41,400	44, 600
March	54,500	67,900	81,200
April	142,400	180,400	167,200
May	415,500	506,400	345,800
June	561,100	652,100	662,000
July	271,500	299,400	440,300
August	144,000	155,900	200,400
September	79,500	87,600	100,900
October	67,700	77,800	82,800
November	54,500	62,800	64,500
December	43,100	49,700	51,200
Total	1,906,600	2,227,700	2,287,300

Table 4.8.--100-year base snowmelt floods for Flaming Gorge and Navajo reservoirs and Lake Powell

Month	100-year base snowmelt floods Flaming Gorge (acre-feet)	Navajo (acre-feet)	Lake Powell (acre-feet)
January	56,200	31,400	691,400
February	66,200	41,400	581,100
March	158, 800	117,500	978,200
April	292,900	298,000	1 , 959,200
May	574,500	501, 600	7,259,500
June	951,600	493,200	6,516,100
July	595,800	205,300	3,594,400
August	254, 900	116,900	1,513,200
September	127,500	89,400	910,800
October	105,800	81,000	456,700
November	86,200	47, 900	408,400
December	57,900	33,000	506,000
Total	3,328,300	2,050, 600	25,375,OOO

5.0 DEPLETION ANALYSIS

5.1 BACKGROUND

Daily snowmelt inflow hydrographs for Glen Canyon (Lake Powell) and Hoover Dam (Lake

Mead) were calculated, along with the intervening inflow between Glen Canyon and Hoover Dams. The 100-year undepleted base snowmelt flood inflow into Hoover Dam has an annual volume of 26,656,000 acre-feet. This inflow hydrograph was separated into hydrographs for each major upstream reservoir to accommodate the modeling requirements for operation of the upstream facilities.

5.2 1985-LEVEL DEPLETIONS ABOVE GLEN CANYON

The 100-year base snowmelt floods are undepleted, unregulated natural flows. The depletions for the Colorado River basin above Glen Canyon Dam (Lake Powell) were obtained from the Upper Colorado Region of the Bureau of Reclamation. The preliminary data, which were used in this study and have since been revised, were used in developing the Colorado River System Consumptive Uses and Losses Report, 1981-1985. Annual depletions for the years 1981 through 1985 were as shown in table 5.1.

Table 5.1 - Annual depletions above Glen Canyon Dam

Year	Depletion (acre-feet)
1981	3,660,600
1982	3,732,800
1983	3,533,700
1984	3,432,100
1985	3,716,500
Total	184,075,700
Average	3,615,100

The 1985-level depletions represent present water resource development conditions in the basin. The 1985-level depletion above Glen Canyon, which is estimated as the 1981-1985 average annual depletion, is 3,615,100 acre-feet. The monthly distribution percentages were estimated by examining a typical irrigated area in the basin (e.g., the Grand Junction area). Data from the irrigation seasons of 1981, 1982, and 1983 were analyzed.The agricultural depletions were typically about 70 percent of the total depletion. Municipal and industrial (M&I) use accounted for the remaining depletions. Depletions for M&I use were distributed evenly throughout the year. Exports from the basin for irrigation and for M&I purposes were also included, and followed the same pattern as was used for the within-basin depletions. The resulting monthly distribution of the depletions was estimated as displayed in table 5.2. The depletions are expected to increase to 4,820,000 acre-feet above Glen Canyon by the year 2010, and to 313,000 acre-feet from Glen Canyon to Hoover, for a total of 5,133,000 acre-feet.

Table 5.2.--Monthly depletions above Glen Canyon Dam

Month	Percent	Depletion (acre-feet)
January	3	108,400
February	2	72,300
March	3	108,500
April	7	253,100
May	11	397,700
June	16	578,400

July	20	723,000
August	18	650,700
September	10	361,500
October	4	144,600
November	3	108,400
December	3	108,500
Total	100	3,615,100

5.3 DEPLETED MONTHLY ANTECEDENT FLOOD FLOW FOR GLEN CANYON

Daily data from the 100-year base snowmelt flood were summarized by month. Using the 1985-level depletions, the 1985-level depleted 100-year base snowmelt flood inflow to Glen Canyon Dam is 21,759,900 acre-feet. The monthly distribution is shown in table 5.3.

Table 5.3.--Monthly 1985-level depleted base snowmelt flood for Glen Canyon Dam

Month	100-year snowmelt flood (acre-feet)	1985-level depletion (acre-feet)	1985-level depleted flow (acre-feet)
January	691,400	108,400	583,000
February	581,100	72,300	508,800
March	978,200	108,500	869,700
April	1,959,200	253,100	1,706,100
May	7,259,500	397,700	6,861,800
June	6,516,100	578,400	5,937,700
July	3,594,400	723,000	2,871,400
August	1,513,200	650,700	862,500
September	910,800	361,500	549,300
October	456,700	144,600	312,100
November	408,400	108,400	300,000
December	506,000	108,500	397,500
Total	25,375,000	3,615,100	21,759,900

5.4 DAILY DEPLETIONS FOR GLEN CANYON DAM

The 100-year base snowmelt flood hydrograph consists of daily values. Therefore, accompanying 1985-level daily depletions were needed to determine the daily 100-year depleted base snowmelt flood for Glen Canyon. The computer program GENHS was developed to produce a balanced hydrograph from known volumes and their associated time periods (e.g., l-, 5-, 10-, 15-, 20-, 30-, 60-, 90-days, etc.). The monthly depletion data were plotted to show the basic hydrograph shape. These monthly volumes were used as input to the program, GENHS, to generate a daily hydrograph of depletions. The resulting hydrograph was adjusted manually to equalize the beginning (January) and ending (December) daily depletions and to smooth the data. The daily depletions were subtracted from the 100-year base snowmelt flood hydrograph to establish the depleted flow conditions. The resulting depleted daily flows and monthly volumes are presented in table 5.4. The 1985-level depleted 100-year base snowmelt flood annual volume is 21,759,600 acre-feet. Monthly volumes, computed from the daily data, are slightly different from those computed from the monthly data because of the hydrograph shaping and smoothing process.

Table 5.4.--100-year inflow hydrograph for Glen Canyon Dam

1985 level depleted 100-year base snowmelt
daily inflow to Glen Canyon Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
0	0	50	8,586	100	20,509	150	156,173
1	8,127	51	8,152	101	21,008	151	150,890
2	8,208	52	7,724	102	21,976	152	145,667
3	8,283	53	7,270	103	22,939	153	141,679
4	8,364	54	6,857	104	23,907	154	137,681
5	8,445	55	6,438	105	24,870	155	133,688
6	8,515	56	5,737	106	25,783	156	129,690
7	8,596	57	5,127	107	26,751	157	126,610
8	8,672	58	4,230	108	27,663	158	123,524
9	8,752	59	3,706	109	28,515	159	120,439
10	8,833	60	4,250	110	29,307	160	117,353
11	8,908	61	4,845	ill	30,103	161	114,273
12	8,989	62	5,445	112	31,485	162	111,182
13	9,065	63	6,196	113	34,313	163	108,072
14	9,145	64	7,855	114	37,368	164	104,966
15	9,226	65	8,989	115	40,570	165	99,662
16	9,302	66	9,453	116	42,738	166	96,673
17	9,382	67	9,912	117	43,862	167	93,693
18	9,458	68	10,376	118	44,991	168	90,729
19	9,539	69	10,834	119	46,146	169	87,779
20	9,619	70	11,298	120	47,376	170	84,795
21	9,695	71	11,787	121	48,495	171	82,057
22	9,776	72	12,922	122	49,503	172	80,781
23	9,871	73	14,318	123	50,517	173	79,753
24	10,088	74	15,170	124	51,525	174	78,644
25	10,325	75	15,488	125	52,538	175	77,509
26	10,562	76	15,800	126	53,557	176	76,370
27	10,804	77	16,108	127	55,170	177	75,241
28	11,036	78	16,420	128	58,271	178	74,101
29	11,273	79	16,738	129	61,437	179	72,967
30	11,510	80	17,046	130	64,598	180	71,833
31	11,555	81	17,343	131	69,271	181	70,844
32	11,505	82	17,646	132	75,553	182	69,866
33	11,414	83	17,948	133	81,835	183	68,813
34	11,318	84	18,326	134	94,469	184	67,704
35	11,228	85	19,188	135	107,764	185	66,594
36	11,132	86	20,071	136	119,824	186	65,490
37	11,036	87	20,943	137	131,883	187	64,311
38	10,945	88	21,336	138	147,583	188	62,949
39	10,819	89	21,220	139	150,350	189	61,780
40	10,678	90	20,943	140	153,113	190	60,807
41	10,532	91	20,711	141	155,881	191	58,699

42	10,391	92	20,665	142	158,644	192	55,417
43	10,245	93	20,620	143	161,407	193	52,065
44	10,103	94	20,575	144	164,134	194	48,707
45	9,962	95	20,524	145	166,771	195	46,836
46	9,816	96	20,479	146	169,408	196	45,732
47	9,675	97	20,434	147	172,039	197	44,628
48	9,443	98	20,444	148	166,751	198	43,499
49	9,019	99	20,479	149	161,462	199	42,314

Table 5.4.--100-year inflow hydrograph for Glen Canyon Dam (continued)

1985 level depleted 100-year base snowmelt
daily inflow to Glen Canyon Dam

Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)	Day	Flow (ft^3/s)
200	41,195	242	10,108	284	5,304	326	5,546
201	40,076	243	9,463	285	5,183	327	5,601
202	39,037	244	9,645	286	5,062	328	5,657
203	38,009	245	10,129	287	4,936	329	5,722
204	37,046	246	10,194	288	4,820	330	5,778
205	36,310	247	10,234	289	4,694	331	5,843
206	34,424	248	10,280	290	4,573	332	5,899
207	31,359	249	10,930	291	4,447	333	5,959
208	28,203	250	10,986	292	4,326	334	6,020
209	25,455	251	10,829	'293	4,205	335	6,166
210	24,275	252	10,789	294	4,084	336	6,226
211	23,448	253	10,577	295	3,963	337	6,272
212	22,627	254	10,517	296	3,837	338	6,292
213	21,633	255	10,355	297	3,716	339	6,312
214	20,570	256	10,088	298	3,590	340	6,332
215	19,506	257	9,715	299	3,474	341	6,352
216	18,447	258	9,241	300	3,348	342	6,373
217	17,383	259	8,717	301	3,227	343	6,398
218	16,340	260	8,349	302	3,106	344	6,418
219	15,281	261	7,920	303	3,146	345	6,438
220	14,243	262	7,835	304	3,358	346	6,458
221	13,673	263	7,744	305	3,615	347	6,478
222	13,582	264	7,754	306	3,882	348	6,499
223	13,496	265	7,663	307	4,114	349	6,524
224	13,406	266	7,623	308	4,341	350	6,544
225	13,320	267	7,532	309	4,537	351	6,564
226	13,280	268	7,492	310	4,628	352	6,584
227	13,249	269	7,401	311	4,679	353	6,604
228	13,219	270	7,361	312	4,734	354	6,625
229	13,184	271	7,270	313	4,784	355	6,650
230	13,154	272	7,225	314	4,840	356	6,670
231	13,118	273	7,134	315	4,895	357	6,690
232	13,083	274	7,295	316	4,951	358	6,690
233	13,058	275	7,255	317	5,011	359	6,690
234	13,022	276	7,220	318	5,072	360	6,690
235	12,992	277	7,179	319	5,127	361	6,695
236	12,957	278	7,013	320	5,193	362	6,695

237	12,927	279	6,731	321	5,248	363	6,695
238	12,896	280	6,408	322	5,304	364	6,695
239	12,483	281	6,110	323	5,369	365	6,695
240	11,686	282	5,823	324	5,425		
241	10,895	283	5,475	325	5,480		

5.5 1985-LEVEL DEPLETIONS FOR RESERVOIRS UPSTREAM FROM GLEN CANYON

The annual depletion data for points upstream from Glen Canyon Dam were obtained from the Upper Colorado Region of the Bureau of Reclamation. These data were for the period 1981 through 1985. No depletion data were received for the area above Navajo Reservoir. There has been very little development, other than some minor transbasin diversions, upstream from this reservoir. Depletions for this area were assumed to be zero. Table 5.5 displays the annual depletions for the major reservoirs upstream from Glen Canyon Dam.

Table 5.5.--1981-1985 annual depletions to major reservoirs upstream from Glen Canyon Dam

	Annual depletions			
Year	Above Blue Mesa (acre-feet)	Above Crystal (acre-feet)	Above Fontanelle (acre-feet)	Above Flaming Gorge (acre-feet)
1981	59,800	68,600	96,400	161,900
1982	60,900	69,900	85,100	152,600
1983	64,400	78,200	116,900	177,400
1984	56,900	66,900	83,800	148,800
1985	71,400	81,400	97,400	154,900
Total	312,900	364,700	479,600	795,600
Average	62,600	72,900	95,900	159,100

The monthly depletion distribution for these areas was assumed to be similar to the distribution for the entire area above Glen Canyon. Using the same monthly depletion distribution percentages as were used for the depletions above Glen Canyon, the monthly 1985-level depletions for these points are as presented in table 5.6.

Table 5.6.--1985-level monthly depletions for the major reservoirs above Glen Canyon Dam

		1985-level monthly depletions			
Month	Monthly percent	Above Blue Mesa (acre-feet)	Above Crystal (acre-feet)	Above Fontenelle (acre-feet)	Above Flaming Gorge (acre-feet)
Jan	3	1,900	2,200	2,900	4,800
Feb	2	1,300	1,40 0	1,900	3,200
Mar	3	1,900	2,200	2,900	4,800

Apr	7	4,400	5,100	6,700	11,100
May	11	6,900	8,000	10,500	17,500
June	16	10,000	11,700	15,300	25,400
July	20	12,500	14,600	19,200	31,800
Aug	18	11,300	13,100	17,300	28,600
Sept	10	6,200	7,300	9,600	15,900
Oct	4	2,500	2,900	3,800	6,400
Nov	3	1,800	2,200	2,900	4,800
Dec	3	1,900	2,200	2,900	4,800
Total	100	62,600	72,900	95,900	159,100

5.6 DEPLETED MONTHLY ANTECEDENT FLOOD INFLOWS FOR RESERVOIRS ABOVE GLEN CANYON

The 1985-level depleted 100-year base snowmelt inflows to Blue Mesa, Crystal, Fontenelle, Flaming Gorge, and Navajo Reservoirs are shown in table 5.7. Monthly depletions were subtracted from the base snowmelt floods to arrive at the 100-year depleted reservoir inflows.

Table 5.7.--1985-level depleted 100-year base snowmelt inflows to the major reservoirs above Glen Canyon

1985-level depleted flow

Month	Blue Mesa (acre-feet)	Crystal (acre-feet)	Fontenelle (acre-feet)	Flaming Gorge (acre-feet)	Navajo (acre-feet)
Jan	36,200	44,100	43,500	51,400	31,400
Feb	33,400	40,000	42,700	63,000	41,400
Mar	52,600	65,700	78,300	154,000	117,500
Apr	138,000	175,300	160,500	281,800	298,000
May	408,600	498,400	335,300	557,000	501,600
June	551,100	640,400	646,700	926,200	493,200
July	259,000	284,800	421,100	564,000	205,300
Aug	132,700	142,800	183,100	226,300	110,900
Sept	73,300	80,300	91,300	111,600	89,400
Oct	65,200	74,900	79,000	99,400	81,000
Nov	52,700	60,600	61,600	81,400	47,900
Dec	41,200	47,500	48,300	53,100	33,000
Total	1,844,000	2,154,800	2,191,400	3,169,200	2,050,600

6.0 BASIN MODELING

6.1 "FHAR" - COMPUTER PROGRAM

Reclamation uses the Flood Hydrograph and Routing (FHAR) computer program to convert excess precipitation to runoff and generate the flood hydrograph for the particular storm event being studied. FHAR, which was developed by Reclamation, uses unitgraph theory. The program derives the flood hydrograph by applying the 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 unit time is computed by dividing the lag time by 5.5.

The subbasin lag times are shown in table 3.1. The unit time selected for this study is one hour, based on the smallest unit times computed for all of the subbasins.

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 inflow, or where costs of obtaining channel cross-section and other data needed for more sophisticated methods are prohibitive. The method uses the travel time of the flood hydrograph for each river reach, the hydrograph ordinates, and the unit time. Development of the travel time was discussed in a previous section of this report.

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. When used to route floods through reservoirs, a fixed elevation-discharge-storage relationship is assumed. The change in storage is accounted for by a change in reservoir water surface elevation. The storage change is equal to the difference between average inflow and average outflow.

6.2 RESERVOIR OPERATING CRITERIA

The reservoirs in the Colorado River basin above Hoover Dam 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.

The 1982 field working agreement between the Bureau of Reclamation and 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 drawdown gradually 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 is routed through the reservoir using predetermined release rates, so that the reservoir system is full by July 1.

During the space-building season, the flood control regulations specify minimum monthly vacant storage requirements for Lake Mead. These requirements may be partially satisfied by considering available storage space in some of the other upstream reservoirs. The vacant storage space requirements in Lake Mead are as follows:

August 1 -	1,500,000	acre-feet
September 1 -	2,270,000	acre-feet
October 1	3,040,000	acre-feet
November 1	3,810,000	acre-feet
December 1	4,580,000	acre-feet
January 1	5,350,000	acre-feet

The regulations allow for Lake Powell, Flaming Gorge plus Fontenelle, Blue Mesa, and Navajo Reservoirs to provide a portion of these requirements. The maximum amount of space creditable to Lake Mead at each of these storage locations is 3,850,000; 1,507,200; 748,500; and 1,035,900 acre-feet, respectively. The system is operated to limit releases at Hoover Dam during the drawdown season to a maximum of 28,000 ft3/s unless modifications are approved by the Corps of Engineers to increase the release.

From January 1 to July 31, during the runoff forecast season, the minimum Lake Mead flood control release requirements are determined from the maximum forecasted inflow volume and the effective storage space in Lake Mead and Lake Powell. The required Hoover Dam flood control release during the current month (Rcm) in ft3/S can be determined from solution of the following algorithm:

$$FI=SSM+SSP+BS+EV - 1\ 500{,}000 + 59.5\ (Rcm+Rrm+Nrm)$$

where, FI is the forecasted inflow volume to Lake Mead in acre-feet during the current month; SSM is the current storage space in Lake Mead in acre-feet below elevation 1229 feet; SSP is the current storage space in Lake Powell in acre-feet below elevation 3700 feet; the bank storage (BS) is equal to 0.065(SSM - 1,500,000); EV is the net evaporation loss to Lake Mead in acre-feet through August 1; Rrm is the Hoover Dam release rate in ft ^{3}/ s during all remaining months through August 1; and N. is the number of remaining months until August 1, excluding the current month.

Lake Mead inflow forecasts are prepared by the Colorado River Forecasting Service and are adjusted to account for effective storage space in upstream reservoirs, flow depletions, and potential forecast errors. Flood control releases below Hoover are made for five discharge levels - 19,000, 28,000, 35,000, 40,000, and 73,000 ft^3/s. The algorithm is solved iteratively to determine the release from Hoover Dam.

The runoff forecast error is computed using relationships derived from an analysis of past Colorado River forecasts and runoff data for the period 1947 to 1983. The data indicate that high runoff years are usually underforecast, and low runoff years are overforecast. In this investigation, the system was operated with a 1 in 20 forecast error, which is defined as a 1 in 20 chance of error or an error of 5 percent. The January forecast error is 5,000,000 acre-feet for Hoover Dam, which is reduced as the season progresses and additional snow depth data are collected. By July, the forecast error has decreased to 750,000 acre-feet. The forecast error is used as an adjustment to forecasted inflows to determine reservoir release rates.

If available flood control storage space diminishes at any time of the year to less than 1,500,000 ac-re-feet, the minimum flood control releases from Lake Mead are determined daily from table 6.1. These releases are determined using available flood control storage space in Lake Mead and inflow to Lake Mead. Some changes to this operating rule are permissible based on the current reservoir release rate, forecasted inflow, and available flood control storage space, as specified in the flood control working agreement.

The upper basin, above Glen Canyon Dam, is operated to avoid spills. It has creditable flood control space (joint use flood control and conservation storage) of about 3.2 million acre-feet in Blue Mesa, Flaming Gorge, Fontenelle, and Navajo Reservoirs. Changes in system operation have historically been made semimonthly in April, May, and June, but are made more frequently if needed.

Table 6.1.--Minimum. flood control releases from Hoover Dam

Water surface elevation (feet)	Release (ft^3/s)
1219.61 - 1221.40	Equal to inflow up to 28,000
1221.40 - 1226.90	Equal to inflow up to 40,000
1226.90 - 1229.00	Equal to inflow up to 65,000
Above 1229.00	Maintain outflow equal to inflow

Notes:
Elevation 1205.30 - Spillway crest elevation
Elevation 1219.61 - Minimum required flood control pool
Elevation 1221.40 - Top of spillway gates in raised position
Elevation 1226.90 - Spillway discharge = 40,000 ft3/s
Elevation 1229.00 - Top of flood control pool
Elevation 1232.00 - Top of dam

6.3 RESERVOIR ROUTING OF 100-YEAR SNOWMELT FLOOD

Using the 100-year depleted snowmelt flood values, two routing studies were performed to simulate reservoir operations during the antecedent flood event. The studies were conducted by the Upper and Lower Colorado Regions using flow information provided by the Denver Office. The first analysis was a bimonthly routing of the flood through the upper and lower basin reservoirs. The second was a daily routing through Lake Powell and Lake Mead during the period of peak inflow.

Several spreadsheets were designed to simulate the monthly planning model, CRSS, used in Colorado River operations. This model is updated bimonthly in response to National Weather Service runoff forecasts. The Colorado River system operation was modeled bimonthly beginning January Ist 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 spreadsheets include the operation of eight reservoirs. For each time period, the reservoir system was operated to fill each of the reservoirs by the end of the runoff period while preserving as much additional release capability as possible for later in the spring. All of the reservoirs had evaporation losses removed from storage. Lake Powell and Lake Mead operations accounted for changes in bank storage. Table 6.2 displays the initial storage conditions on January 1 which were used in this study.

The initial Lake Mead storage condition was chosen to achieve a total system space of approximately 5.35 million acre-feet, which represents a realistic starting point under full reservoir conditions. Initial storage conditions for Lakes Mohave and Havasu were taken from their respective operating rule curves.

Table 6.2.--January 1 reservoir storage capacities

Reservoir	Storage (acre-feet)
Fontenelle	200,000
Flaming Gorge	3,200,000
Blue Mesa	545,000
Navajo	1,550,000
Lake Powell	22,600,000
Lake Mead	24,550,000
Lake Mohave	1,582,000
Lake Havasu	539,100

Release decisions were based on the current operating philosophy of avoiding spills by incorporating changes in the forecasted runoff as soon as possible, thus preserving future operational flexibility.

The operating objectives were to limit releases from Lake Mead to a maximum of 40,000 ft^3/s and to maintain as nearly as practicable, a non-fluctuating flow regime below Parker Dam. In the case of Glen Canyon Dam, an upper limit release of 31,500 ft^3/s was observed until published forecasts indicated a high risk of bypass of the powerplant, at which time the release was increased to the powerplant capacity of 33,100 ft^3/s. As in actual practice, bypasses were delayed when the possibility of not needing them existed.

This analysis showed that the 100-year snowmelt flood can be routed through Lake Mead without exceeding a release level of 40,000 ft^3/s and without exceeding elevation 1,219.6 feet, the bottom of the exclusive flood control pool. Flood control releases of 29,500 ft^3/s would be initiated on January 1 and gradually increase to a maximum of 40,000 ft^3/s by July 1. The maximum release would continue through July 15, followed by a gradual reduction in release levels coinciding with the flood's recession. A maximum water surface elevation of 1,219.5 feet would occur on July 19 through July 21.

At Lake Powell the releases from the dam were 31,500 ft^3/s from January 1 through April 30, 33,100 ft^3/s from May 1 through June 7, 48,000 ft^3/s from June 8 through June 14, and 60,000 ft^3/s from June 15 through July 12. After this time, the releases gradually decreased as the flood passed. The maximum water surface elevation of 3,699.93 feet occurred on July 8.

Based on the results of the base snowmelt flood routings, beginning reservoir elevations were determined for all of the major reservoirs upstream from Hoover Dam for use in routing the flood caused by the ULDRS event. Table 6.3 presents the starting reservoir elevations for Lake Mead and Lake Powell based upon the starting date of the ULDRS event. The upstream reservoirs were considered at the top of conservation storage.

6.4 GLEN CANYON AND HOOVER PROBABLE MAXIMUM FLOODS

Determination of the probable maximum floods for Hoover and Glen Canyon Dams 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 seasonal hydrologic conditions for the dam. The ULDRS flood hydrographs were combined with the snowmelt antecedant flood to determine the most critical hydrologic condition at the dams. Results of these analyses produced PMFs for the critical May through August storm season.

Table 6.3.--Initial reservoir elevations for routing the ULDRS flood through Lake Mead and Lake Powell

Lake	ULDRS starting date	Reservoir elevation (feet)
Powell	May 15	3666.1
	June 15	3698.6
	July 15	3699.8
	August 15	3699.1
Mead	May 15	1210.1
	June 15	1211.3
	July 15	1219.0
	August 15	1217.5

The most critical combination of ULDRS events with the snowmelt flood was determined from reservoir routings. Many possible combinations were tried in order to arrive at the one which produced the highest reservoir elevation. The FHAR computer model was used to compute the flood hydrographs beginning the fifteenth day of May, June, July, and August for each storm combination. The following combinations of storm centerings were evaluated: (1) San Juan followed by Cedar Mountain, (2) San Juan followed by Boulder, (3) Boulder followed by San Juan, and (4) Cedar Mountain followed by San Juan. The Boulder and Cedar Mountain storm centerings were not examined in combination because their close proximity precluded them from occurring within 7 days of each other with magnitudes approaching ULDRS events.

The full ULDRS events, which could occur during the August through October time period, were adjusted downward to account for seasonal variations and separation time between storms. Adjustments were made for storms separated by 1, 3, 5, and 7 days. The first storm in the sequence always had the full ULDRS magnitude less the applicable seasonal adjustment, and the second storm was adjusted for both seasonal variation and days between storms. Individual ULDRS events were also centered over the basin to determine the flows at each dam. The numerous combinations of storm centers, storm separation times, and seasonal variations in rainfall magnitudes produced 76 possible flood events for evaluation and comparison.

The San Juan storm centering followed by the Boulder storm produced the most critical flood condition at Glen Canyon Dam. Table 6.4 shows the results of this flood analysis. The maximum inflow, outflow, and reservoir elevation are presented for several storm separation intervals and starting dates. The most critical conditions based on the highest reservoir elevations are highlighted and represent the probable maximum floods for the dam. Tables 6.5 through 6.8 list the PMF hydrograph ordinates for each of the floods, and Figures 6.1 through 6.4 show the corresponding hydrographs.

Table 6.4.--Glen Canyon Dam routing results for San Juan storm followed by the Boulder storm

Start date	Lag (days)	Maximum inflow (ft3/S)	60-day volume (106 ac-ft)	Maximum outflow (ft3/S)	Starting reservoir elev (ft)	Maximum reservoir elev (ft)
May 15	1	547,000	15.945	168,000	3666.1	3700.9
	3	547,000	16.048	170,000	3666.1	3700.9
	5	547,000	16.485	180,000	3666.1	3701.0
	7	5 5 51 (00	16.309	180,000	3666.1	3702
June 15	1.	525 000	9. .7 2 6	180 000	3698.6	3708.9
	3	525,000	9.860	180,000	3698.6	3707.7
	5	544,000	10.026	180,000	3698.6	3707.3
	7	610,000	10.196	180,000	3698.6	3707.3
July 15	1 ..	560fOOO	6.737	180,000	3699.8	3709.4
	3	612,000	6.921	180,OOO	3699.8	3707.5
	5	661,000	7.082	180,000	3699.8	3707.4
	7	726,000	7.284	180,000	3699.8	3707.4
August 15	1	697 000		180, 000	3699.0	3709.8
	3	724,000	5.861	180,000	3699.0	3707.1
	5	793,000	6.083	180,000	3699.0	3706.7
	7	869,000	6.319	180,000	3699.0	3706.7

Table 6.5. -- Glen Canyon Dam probable maximum flood for May

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	113,990	300	433,196	600	126,115	900	90,179
6	113,990	306	411,812	606	126,115	906	90,179
12	113,990	312	385,357	612	126,115	912	89,206
18	113,990	318	286,470	618	126,115	918	89,206
24	126,115	324	247,228	624	123,085	924	89,206
30	126,115	330	232,723	630	123,085	930	89,206
36	126,115	336	213,127	636	123,085	936	88,228
42	126,115	342	199,199	642	123,085	942	88,228
48	140,274	348	189,499	648	120,050	948	88,228
54	473,405	354	183,528	654	120,050	954	88,228
60	333,225	360	175,341	660	120,050	960	87,250
66	467,744	366	173,402	666	120,050	966	87,250
72	496,877	372	171,909	672	117,020	972	87,250
78	526,525	378	170,842	678	117,020	978	87,250
84	534,587	384	165,203	684	117,020	984	86,272
90	543,669	390	164,817	690	117,020	990	86,272
96	470,351	396	164,504	696	113,990	996	86,272
102	363,295	402	164,234	702	113,990	1002	86,272
108	291,899	408	158,904	708	113,990	1008	85,299
114	252,854	414	158,717	714	113,990	1014	85,299
120	234,241	420	158,530	720	108,737	1020	85,299
126	220,636	426	157,726	726	108,737	1026	85,299
132	210,877	432	151,489	732	108,737	1032	84,321
138	203,693	438	150,271	738	108,737	1038	84,321
144	200,637	444	150,145	744	105,803	1044	84,321
150	196,040	450	150,127	750	105,803	1050	84,321
156	192,331	456	146,157	756	105,803	1056	83,343
162	189,158	462	146,130	762	105,803	1062	83,343
168	189,223	468	146,126	768	102,874	1068	83,343
174	186,972	474	146,126	774	102,874	1074	83,343
180	185,030	480	142,183	780	102,874	1080	82,370
186	183,287	486	142,183	786	102,874	1086	82,370
192	184,656	492	142,183	792	99,945	1092	82,370
198	183,159	498	142,183	798	99,945	1098	82,370
204	181,913	504	138,240	804	99,945	1104	81,391
210	180,936	510	138,240	810	99,945	1110	81,391
216	182,919	516	138,240	816	97,015	1116	81,391
222	182,146	522	138,240	822	97,015	1122	81,391'
228	181,555	528	135,210	828	97,015	1128	80,413
234	181,017	534	135,210	834	97,015	1134	80,413
240	182,612	540	135,210	840	94,086	1140	80,413
246	178,028	546	135,210	846	94,086	1146	80,413
252	174,293	552	132,180	852	94,086	1152	79,440
258	173,821	558	132,180	858	94,086	1158	79,440
264	176,642	564	132,180	864	91,399	1164	79,440
270	176,642	570	132,180	870	91,399	1170	79,440
276	176,642	576	129,145	876	91,399	1176	78,462
282	176,642	582	129,145	882	91,399	1182	78,462

288	181,683	588	129,145	888	90,179	1188	78,462
294	554,330	594	129,145	894	90,179	1194	78,462

Table 6.5.--Glen Canyon Dam probable maximum flood for May (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	77,484	1260	75,533	1320	72,604	1380	67,270
1206	77,484	1266	75,533	1326	72,604	1386	67,270
1212	77,484	1272	74,555	1332	72,604	1392	64,038
1218	77,484	1278	74,555	1338	72,604	1398	64,038
1224	76,506	1284	74,555	1344	70,497	1404	64,038
1230	76,506	1290	74,555	1350	70,497	1410	64,038
1236	76,506	1296	73,577	1356	70,497	1416	60,872
1242	76,506	1302	73,577	1362	70,497	1422	60,872
1248	75,533	1308	73,577	1368	67,270	1428	60,872
1254	75,53 3	1314	73,577	1374	67,270	1434	60,872

Table 6.6.--Glen Canyon Dam probable maximum flood for June

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	105,803	300	84,378	600	70,497	900	50,577
6	105,803	306	84,365	606	70,497	906	50,577
12	105,803	312	83,366	612	70,497	912	49,498
18	105,803	318	83,346	618	70,497	918	49,498
24	102,874	324	83,343	624	67,270	924	49,498
30	102,874	330	83,343	630	67,270	930	49,498
36	102,874	336	82,370	636	67,270	936	48,425
42	102,874	342	82,370	642	67,270	942	48,425
48	102,170	348	82,370	648	64,038	948	48,425
54	466,490	354	82,370	654	64,038	954	48,425
60	317,272	360	81,391	660	64,038	960	46,307
66	457,335	366	.81,391	666	64,038	966	46,307
72	470,227	372	81,391	672	60,872	972	46,307
78	502,472	378	81,391	678	60,872	978	46,307
84	511,278	384	80,413	684	60,872	984	43,156
90	521,546	390	80,413	690	60,872	990	43,156
96	436,031	396	80,413	696	59,193	996	43,156
102	319,239	402	80,413	702	59,193	1002	43,156
108	242,765	408	79,440	708	59,193	1008	40,000
114	201,190	414	79,440	714	59,193	1014	40,000
120	173,338	420	79,440	720	58,114	1020	40,000
126	157,652	426	79,440	726	58,114	1026	40,000
132	146,938	432	78,462	732	58,114	1032	36,915
138	139,105	438	78,462	738	58,114	1038	36,915
144	133,390	444	78,462	744	57,036	1044	36,915
150	450,209	450	78,462	750	57,036	1050	36,915
156	341,023	456	77,484	756	57,036	1056	35,276
162	315,878	462	77,484	762	57,036	1062	35,276
168	293,205	468	77,484	768	55,962	1068	35,276
174	203,145	474	77,484	774	55,962	1074	35,276

180	167,855	480	76,506	780	55,962	1080	34,222
186	154,632	486	76,506	786	55,962	1086	34,222
192	140,784	492	76,506	792	54,883	1092	34,222
198	128,334	498	76,506	798	54,883	1098	34,222
204	119,465	504	75,533	804	54,883	1104	33,174
210	113,662	510	75,533	810	54,883	1110	33,174
216	109,309	516	75,533	816	53,809	1116	33,174
222	106,970	522	75,533	822	53,809	1122	33,174
228	105,169	528	74,555	828	53,809	1128	32,120
234	103,749	534	74,555	834	53,809	1134	.32,120
240	101,060	540	74,555	840	52,730	1140	32,120
246	95,895	546	74,555	846	52,730	1146	32,120
252	91,676	552	73,577	852	52,730	1152	31,071
258	90,754	558	73,577	858	52,730	1158	31,071
264	87,967	564	73,577	864	51,651	1164	31,071
270	85,952	570	73,577	870	51,651	1170	31,071
276	85,548	576	72,604	876	51,651	1176	30,018
282	85,492	582	72,604	882	51,651	1182	30,018
288	84,467	588	72,604	888	50,577	1188	30,018
294	84,408	594	72,604	894	50,577	1194	30,018

Table 6.6.--Glen Canyon Dam probable maximum flood for June (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	28,969	1260	26,867	1320	24,200	1380	24,028
1206	28,969	1266	26,867	1326	24,200	1386	24,028
1212	28,969	1272.	25,818	1332	24,200	1392	23,943
1218	28,969	1278	25,818	1338	24,200	1398	23,943
1224	27,920	1284	25,818	1344	24,114	1404	23,943
1230	27,920	1290	25,818	1350	24,114	1410	23,943
1236	27,920	1296	24,764	1356	24,114	1416	23,862
1242	27,920	1302	24,764	1362	24,114	1422	23,862
1248	26,867	1308	24,764	1368	24,028	1428	23,862
1254	26,867	1314	24,764	1374	24,028	1434	23,862

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	58,114	300	44,451	600	24,200	900	23,630
6	58,114	306	44,348	606	24,200	906	23,630
12	58,114	312	40,940	612	24,200	912	23,600
18	58,114	318	39,204	618	24,200	918	23,600
24	57,036	324	37,264	624	24,114	924	23,600
30	57,036	330	36,923	630	24,114	930	23,600

36	57,036	336	35,276	636	24,114	936	23,574
42	57,036	342	35,276	642	24,114	942	23,574
48	58,515	348	35,276	648	24,028	948	23,574
54	476,820	354	35,276	654	24,028	954	23,574
60	313,449	360	34,222	660	24,028	960	23,544
66	463,032	366	34,222	666	24,028	966	23,544
72	482,973	372	34,222	672	23,943	972	23,544
79	518,992	378	34,222	678	23,943	978	23,544
84	528,966	384	33,174	684	23,943	984	23,514
90	541,944	390	33,174	690	23,943	990	23,514
96	447,640	396	33,174	696	23,862	996	23,514
102	312,970	402	33,174	702	23,862	1002	23,514
108	224,447	408	32,120	708	23,862	1008	23,489
114	177,780	414	32,120	714	23,862	1014	23,489
120	150,390	420	32,120	720	23,827	1620	23,489
126	132,202	426	32,120	726	23,827	1026	23,489
132	117,381	432	31,071	732	23,827	1032	23,080
138	107,275	438	31,071	738	23,827	1038	23,080
144	101,486	444	31,071	744	23,801	1044	23,080
150	551,911	450	31,071	750	23,801	1050	23,080
156	401,257	456	30,018	756	23,801	1056	22,289
162	377,743	462	30,018	762	23,801	1062	22,289
168	347,571	468	30,018	768	23,771	1068	22,289
174	228,013	474	30,018	774	23,771	1074	22,289
180	176,138	480	28,969	780	23,771	1080	21,502
186	153,273	486	28,969	786	23,771	1086	21,502
192	129,852	492	28,969	792	23,741	1092	21,502
198	108,592	498	28,969	798	23,741	1098	21,502
204	93,483	504	27,920	804	23,741	1104	20,716
210	83,943	510	27,920	810	23,741	1110	20,716
216	77,350	516	27,920	816	23,716	1116	20,716
222	73,546	522	27,920	822	23,716	1122	20,716
228	70,640	528	26,867	828	23,716	1128	20,076
234	68,492	534	26,867	834	23,716	1134	20,076
240	64,649	540	26,867	840	23,685	1140	20,076
246	60,176	546	26,867	846	23,685	1146	20,076
252	54,065	552	25,818	852	23,685	1152	19,798
258	52,308	558	25,818	858	23,685	1158	19,798
264	48,761	564	25,818	864	23,655	1164	19,798
270	48,489	570	25,818	870	23,655	1170	19,798
276	48,269	576	24,764	876	23,655	1176	19,536
282	48,092	582	24,764	882	23,655	1182	19,536
288	44,770	588	24,764	888	23,630	1188	19,536
294	44,586	594	24,764	894	23,630	1194	19,536

Table 6.7.--Glen Canyon Dam probable maximum flood for July (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	19,274	1260	18,745	1320	17,958	1380	17,434
1206	19,274	1266	18,745	1326	17,958	1386	17,434
1212	19,274	1272	18,482	1332	17,958	1392	17,172

1218	19,274	1278	18,482	1338	17,958	1398	17,172
1224	19,007	1284	18,482	1344	17,696	1404	17,172
1230	19,007	1290	18,482	1350	17,696	1410	17,172
1236	19,007	1296	18,220	1356	17,696	1416	16,910
1242	19,007	1302	18,220	1362	17,696	1422	16,910
1248	18,745	1308	18,220	1368	17,434	1428	16,910
1254	18,745	1314	18,220	1374	17,434	1434	16,910

Table 6.8 - Glen Canyon Dam probable maximum flood for August

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	23,801	300	32,786	600	17,696	900	13,048
6	23,801	306	32,299	606	17,696	906	13,048
12	23,801	312	31,034	612	17,696	912	12,856
18	23,801	318	30,582	618	17,696	918	12,856
24	23,771	324	.30,205	624	17,434	924	12,856
30	23,771	330	29,881	630	17,434	930	12,856
36	23,771	336	28,803	636	17,434	936	12,664
42	23,771	342	28,526	642	17,434	942	12,664
48	26,513	348	28,261	648	17,172	948	12,664
54	480,826	354	28,012	654	17,172	954	12,664
60	309,907	360	27,001	660	17,172	960	12,473
66	465,555	366	26,777	666	17,172	966	12,473
72	489,845	372	26,108	672	16,910	972	12,473
78	528,414	378	23,320	678	16,910	978	12,473
84	539,262	384	20,373	684	16,910	984	12,281
90	555,572	390	20,080	690	16,910	990	12,281
96	456,691	396	20,076	696	16,491	996	12,281
102	308,332	402	20,076	702	16,491	1002	12,281
108	209,963	408	19,798	708	16,491	1008	12,090
114	158,873	414	19,798	714	16,491	1014	12,090
120	131,094	420	19,798	720	15,916	1020	12,090
126	113,867	426	19,798	726	15,916	1026	12,090
132	100,931	432	19,536	732	15,916	1032	11,898
138	89,031	438	19,536	738	15,916	1038	11,898
144	82,628	444	19,536	744	15,342	1044	11,898
150	679,374	450	19,536	750	15,342	1050	11,898
156	488,865	456	19,274	756	15,342	1056	11,707
162	467,433	462	19,274	762	15,342	1062	11,707
168	431,303	468	19,274	768	14,767	1068	11,707
174	281,224	474	19,274	774	14,767	1074	11,707
180	209,052	480	19,007	780	14,767	1080	11,515
186	174,386	486	19,007	786	14,767	1086	11,515
192	140,211	492	19,007	792	14,197	1092	11,515
198	107,763	498	19,007	798	14,197	1098	11,515
204	84,519	504	18,745	804	14,197	1104	11,323
210	69,847	510	18,745	810	14,197	1110	11,323
216	61,130	516	18,745	816	13,668	1116	11,323
222	55,091	522	18,745	822	13,668	1122	11,323
228	50,365	528	18,482	828	13,668	1128	11,132
234	46,785	534	18,482	834	13,668	1134	11,132
240	44,185	540	18,482	840	13,431	1140	11,132
246	42,101	546	18,482	846	13,431	1146	11,132

252	40,362	552	18,220	852	13,431	1152	10,940
258	38,943	558	18,220	858	13,431	1158	10,940
264	37,695	564	18,220	864	13,239	1164	10,940
270	36,713	570	18,220	870	13,239	1170	10,940
276	35,884	576	17,958	876	13,239	1176	10,754
282	35,140	582	17,958	882	13,239	1182	10,754
288	34,046	588	17,958	888	13,048	1188	10,754
294	33,365	594	17,958	894	13,048	1194	10,754

Table 6.8.--Glen Canyon Dam probable maximum flood for August (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	10,562	1260	9,811	1320	8,500	1380	7,714
1206	10,562	1266	9,811	1326	8,500	1386	7,714
1212	10,562	1272	9,372	1332	8,500	1392	7,557
1218	10,562	1278	9,372	1338	8,500	1398	7,557
1224	10,245	1284	9,372	1344	8,067	1404	7,557
1230	10,245	1290	9,372	1350	8,067	1410	7,557
1236	10,245	1296	8,939	1356	8,067	1416	7,411
1242	10,245	1302	8,939	1362	8,067	1422	7,411
1248	9,811	1308	8,939	1368	7,714	1428	7,411
1254	9,811	1314	8,939	1374	7,714	1434	7,411

The most critical flood situation for Hoover Dam occurs when the San Juan storm is followed by the 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. Table 6.9 presents the results of this analysis for several storm separation times. Tables 6.10 through 6.13 list the hydrograph ordinates for the highlighted floods shown on table 6.9 and figures 6.5 through 6.8 present the corresponding hydrographs. These are the seasonal PMFs for Hoover Dam based upon the flood routings.

Table 6.9.-- Hoover Dam routing results for San Juan storm followed by the Cedar Mountain storm

Start date	Lag (days)	Maximum inflow (ft^3/s)	Total volume (106 ac-ft)	Maximum outflow (ft^3/s)	Starting reservoir elev (ft)	Maximum reservoir elev (ft)
May 15	1	310,000	13.392	125,000	1210.1	1229.6
	3	371,000	13.522	127,000	1210.1	1229.6
	5	445,000	13.692	130,000	1210.1	1229.6
	7	506,000	13.845	132,006	1210.1	1229.6
June 15	1	585,000	12.399	183,000	1211.3	1230.1
	3	650,000	12.559	189,000	1211.3	1230.1
	5	727,000	12.767	227,000	1211.3	1230.5
	7	805,000	12.999	302 000	1211.3	1231.1
July 15	1	763,000	10.440	240,000	1219.0	1230.6
	3	848,000	10.706	324,000	1219.0	1231.3
	5	919 000	10.945	401,000	1219.0	1232.4
	7	949,000	11.240	4011000	1219.0	1232.3

August15	1	988,000	10.490	275,000	1217.5	1230.9
	3	1,049,000	10.715	352,000	1217.5	1231.6
	5	1,144,000	11.055	401,000	1217.5	1232.8
	7	1,130 000	11.384	402,000	1217.5	1233.0

Table 6.10.--Hoover Dam probable-maximum flood for May

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	1,553	300	152,678	600	135,539	900	95,231
6	1,553	306	138,632	606	134,516	906	94,687
12	1,559	312	122,061	612	133,639	912	94,227
18	2,859	318	131,080	618	132,988	918	93,693
24	18,269	324	139,204	624	132,252	924	93,253
30	33,513	330	130,962	630	131,274	930	92,931
36	34,813	336	129,790	636	130,419	936	92,649
42	34,819	342	144,708	642	129,779	942	92,280
48	34,986	348	157,146	648	129,042	948	91,970
54	34,986	354	165,690	654	128,069	954	91,742
60	34,986	360	171,646	660	127,228	960	91,526
66	34,987	366	174,643	666	126,597	966	91,205
72	35,207	372	176,177	672	125,874	972	90,928
.78	35,418	378	177,132	678	124,909	978	90,724
84	36,503	384	177,162	684	124,067	984	90,531
90	37,608	390	176,249	690	123,428	990	90,222
96	37,844	396	175,148	696	122,712	996	89,954
102	36,977	402	174,195	702	121,751	1002	89,756
108	36,082	408	172,919	708	120,913	1008	89,562
114	35,694	414	171,138	714	120,297	1014	89,256
120	35,543	420	169,518	720	119,607	1020	88,990
126	35,433	426	168,271	726	118,646	1026	88,794
132	35,370	432	166,866	732	117,812	1032	88,601
138	35,333	438	165,023	738	117,187	1038	88,297
144	35,343	444	163,402	744	116,410	1044	88,033
150	35,323	450	162,161	750	114,989	1050	87,838
156	35,316	456	160,874	756	113,659	1056	87,646
162	35,316	462	-159,327	762	112,632	1062	87,341
168	35,357	468	158,002	768	111,806	1068	87,076
174	35,357	474	156,977	774	110,717	1074	86,881
180	35,357	480	155,848	780	109,798	1080	86,689
186	35,357	486	154,427	786	109,121	1086	86,384
192	35,392	492	153,195	792	108,486	1092	86,119
198	35,392	498	152,253	798	107,526	1098	85,923
204	35,392	504	151,208	804	106,699	1104	85,732
210	35,392	510	149,844	810	106,090	1110	85,428
216	35,432	516	148,654	816	105,498	1116	85,164
222	35,432	522	147,757	822	104,572	1122	84,969
228	35,432	528	1,6,748	828	103,770	1128	84,782
234	35,432	534	145,418	834	103,178	1134	94,478
240	35,473	540	144,259	840	102,602	114.0	84,213
246	35,473	546	143,384	846	101,686	1146	84,017
252	35,473	552	142,476	852	100,889	1152	83,825

258	35,473	558	141,360	858	100,302	1158	83,520
264	35,509	564	140,400	864	99,725	1164	83,255
270	35,509	570	139,683	870	98,811	1170	83,059
276	48,420	576	138,886	876	98,017	1176	82,867
282	466,167	582	137,860	882	97,431	1182	82,563
288	244,438	588	136,965	888	96,838	1188	82,299
294	202,695	594	136,297	894	95,976	1194	82,104

Table 6.11.-- Hoover Dam probable maximum flood for June

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	1,598	300	354,117	600	77,143	900	61,709
6	1,598	306	328,326	606	76,749	906	61,117
12	1,607	312	296,215	612	76,421	912	60,472
18	3,584	318	289,643	618	76,169	918	59,849
24	27,322	324	286,564	624	75,761	924	59,261
30	53,437	330	266,435	630	75,177	930	58,718
36	59,356	336	244,601	636	74,646	936	58,171
42	62,170	342	230,892	642	74,242	942	57,643
48	63,857	348	217,312	648	73,783	948	57,143
54	65,216	354	195,467	654	73,480	954	56,68O
60	66,510	360	170,O66	660	73,329	960	56,243
66	67,789	366	149,730	666	73,I86	966	55,784
72	72,201	372	134,556	672	72,955	972	55,346
78	108,899	378	123,457	678	72,741	978	54,941
84	167,600	384	115,138	684	72,514	984	54,566
90	184,952	390	108,751	690	72,277	990	54,091
96	185,973	396	103,838	696	72,003	996	53,623
102	184,571	402	100,119	702	71,716	1002	53,189
108	183,170	408	97,199	708	71,419	1008	52,765
114	182,564	414	94,771	714	71,136	1014	52,201
120	182,326	420	92,848	720	70,828	1020	51,637
126	182,I54	426	91,384	726	70,512	1026	51,113
132	182,055	432	90,172	732	70,201	1032	50,607
138	181,997	438	89,036	738	69,902	1038	49,966
144	181,982	444	88,102	744	69,576	1044	49,332
150	181,951	450	87,355	750	69,271	1050	48,744
156	181,941	456	86,701	756	68,898	1056	48,160
162	181,940	462	86,001	762	68,486	1062	47,469

168	181,960	468	85,415	768	68,171	1068	46,790
174	181,960	474	84,923	774	67,877	1074	46,161
180	181,960	480	84,458	780	67,587	1080	45,561
186	181,960	486	83,911	786	67,305	1086	44,926
192	181,980	492	83,440	792	67,004	1092	44,319
198	181,980	498	83,052	798	66,713	1098	43,758
204	181,980	504	82,690	804	66,425	1104	43,236
210	181,980	510	82,215	810	66,145	1110	42,695
216	181,999	516	81,796	816	65,841	1116	42,182
222	181,999	522	81,464	822	65,552	1122	41,709
228	181,999	528	81,137	828	65,266	1128	41,262
234	181,999	534	80,706	834	64,988	1134	40,795
240	182,025	540	80,327	840	64,691	1140	40,351
246	182,025	546	80,019	846	64,404	1146	39,940
252	182,025	552	79,723	852	64,119	1152	39,556
258	182,025	558	79,318	858	63,843	1158	39,143
264	182,045	564	78,961	864	63,543	1164	38,747
270	182,044	570	78,684	870	63,257	1170	38,382
276	198,827	576	78,410	876	62,974	1176	38,039
282	765,356	582	78,032	882	62,699	1182	37,664
288	463,560	586	77,696	888	62,405	1188	37,304
294	416,190	594	77,437	894	62,113	1194	36,971

Table 6.11. - Hoover Dam probable maximum flood for June (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	36,653	1458	33,104	1716	33,103	1974	33,103
1206	36,305	1464	33,104	1722	33,103	1980	33,103
1212	35,970	1470	33,104	1728	33,103	1986	33,103
1218	35,660	1476	33,104	1734	33,103	1992	33,103

1224	35,386	1482	33,104	1740	33,103	1998	33,103
1230	35,211	1488	33,104	1746	33,103	2004	33,103
1236	35,186	1494	33,104	1752	33,103	2010	33,103
1242	35,186	1500	33,104	1758	33,103	2016	33,103
1248	35,201	1506	33,104	1764	33,103	2022	33,103
1254	35,201	1512	33,104	1770	33,103	2028	33,103
1260	35,201	1518	33,104	1776	33,103	2034	33,1O3
1266	35,201	1524	33,104	1782	33,103	2040	33,103
1272	35,211	1530	33,164	.1788	33,103	2046	33,103
1278	35,211	1536	33,104	1794	33,103	2052	33,103
1284	35,211	1542	33,104	1800	33,103	2058	33,103
1290	35,211	1548	33,104	1806	.3 3,103	2064	33,103
1296	35,227	1554	33,104	1812	33,103	2070	33,103
1302	35,227	1560	33,104	1818	33,103	2076	33,103
1308	35,227	1566	33,104	1824	33,103	2082	33,103
1314	35,227	1572	33,104	1830	33,103	2088	33,103
1320	35,216	1578	33,104	1836	33.103	2094	33,103
1326	35,216	1584	33,104	1842	33,103	2100	33,103
1332	35,216	1590	33,104	1848	33,103	2106	33,103
1338	35,216	1596	33,104	1854	33,103	2112	33,103
1344	35,186	1602	33,104	1860	33,103	2118	33,103
1350	35,186	1608	33,104	1866	33,103	2124	33,103
1356	35,186	1614	33,104	1872	33,103	2130	33,103
1362	35,186	1620	33,104	1878	33,103	2136	33,103
1368	35,156	1626	33,104	1884	33,103	2142	33,103
1374	35,156	1632	33,104	1890	33,103	2148	33,102
1380	35,156	1638	33,104	1896	33,103	2154	33,102
1386	35,156	1644	33,103	1902	33,103	2160	33,102
1392	35,121	1650	33,103	1908	33,103	2166	33,102
1398	35,121	1656	33,103	1914	33,103	2172	33,091
1404	35,121	1662	33,103	1920	33,103	2178	31,259
1410	35,121	1668	33,103	1926	33,103		
1416	35,095	1674	33,103	1932	33,103		
1422	35,095	1680	33,103	1938	33,103		
14.28	35,095	1686	33,103	1944	33,103		
1434	35,095	1692	33,103	1950	33,103		
1440	33,104	1698	33,103	1956	33,103		
1446	33,104	1704	33,103	1962	33,103		
1452	33,104	1710	33,103	1968	33,103		

Table 6.12.--Hoover Dam probable maximum flood for July

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	*2,042*	*300*	*229,321*	*600*	*35,924*	*900*	*35,010*
6	*2,042*	*306*	*199,754*	*606*	*35,881*	*906*	*35,010*
12	*2,054*	*312*	*164,186*	*612*	*35,852*	*912*	*34,995*
is	*4,749*	*318*	*135,560*	*618*	*35,815*	*918*	*34,995*
24	*36,276*	*324*	*114,308*	*624*	*35,749*	*924*	*34,995*
30	*67,635*	*330*	*98,893*	*630*	*35,719*	*930*	*34,995*
36	*70,001*	*336*	*89,341*	*636*	*35,689*	*936*	*34,985*
42	*69,688*	*342*	*85,483*	*642*	*35,642*	*942*	*34,985*
48	*69,344*	*348*	*83,008*	*648*	*35,585*	*948*	*34,985*

54	69,011	354	80,790	654	35,560	954	34,985
60	68,684	360	78,717	660	35,536	960	34,974
66	68,429	366	76,756	666	35,520	966	34,974
72	70,898	372	74,945	672	35,468	972	34,974
78	101,258	378	73,309	678	35,444	918	34,974
84	162,392	384	71,776	684	35,425	984	34,964
90	187,030	390	70,301	690	35,410	990	34,964
96	188,870	396	68,914	696	35,366	996	34,964
102	186,484	402	67,346	702	35,355	1002	34,964
108	184,192	408	65,198	708	35,261	1008	34,954
114	183,316	414	62,916	714	35,111	1014	34,954
120	183,085	420	60,814	720	35,080	1020	34,954
126	183,009	426	58,858	726	35,080	1026	34,954
132	182,725	432	57,037	732	35,080	1032	34,959
138	182,379	438	55,302	738	35,080	1038	34,959
144	182,136	444	53,702	744	35,070	1044	34,959
150	182,021	450	52,220	750	35,070	1050	34,959
156	181,975	456	50,849	756	35,070	1056	34,979
162	181,956	462	49,514	762	35,070	1062	34,979
168	181,924	468	48,271	768	35,060	1068	34,979
174	181,915	474	47,131	774	35,060	1074	34,979
180	181,909	480	46,058	780	35,060	1080	35,000
186	181,904	486	45,011	786	35,060	1086	35,000
192	181,879	492	44,034	792	35,050	1092	35,000
198	181,876	498	43,124	798	35,050	1098	35,000
	181,874	504	42,280	804	35,050	1104	35,020
210	181,872	510	41,438	810	35,050	1110	35,020
216	181,845	516	40,648	816	35,040	1116	35,020
222	181,844	522	39,923	822	35,040	1122	35,020
228	201,551	528	39,242	828	35,040	1128	35,035
234	880,565	534	38,558	834	35,040	1134	35,035
240	521,096	540	37,909	840	35,030	1140	35,035
246	469,550	546	37,313	846	35,030	1146	35,035
252	399,448	552	36,766	852	35,030	1152	35,045

258	*366,407*	*558*	*36,355*	*858*	*35,030*	*1158*	*35,045*
264	*327,503*	*564*	*36,228*	*864*	*35,020*	*1164*	*35,045*
270	*317,132*	*570*	*36,165*	*870*	*35,020*	*1170*	*35,045*
276	*311,927*	*576*	*36,129*	*876*	*35,020*	*1176*	*35,050*
282	*288,000*	*582*	*36,080*	*882*	*35,020*	*1182*	*35,050*
288	*262,947*	*588*	*36,032*	*888*	*35,010*	*1188*	*35,050*
294	*247,088*	*594*	*35,983*	*894*	*35,010*	*1194*	*35,050*

Table 6.12.-- Hoover Dam probable maximum flood for July (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
Hour	(ft3/s)	Hour	(ft3/s)	Hour	(ft3/s)	Hour	(ft3/s)
1200	35,055	1458	33,103	1716	33,103	1974	33,102
1206	35,055	1464	33,103	1722	33,103	1980	33,102
1212	35,055	1470	33,103	1728	33,103	1986	33,102
1218	35,055	1476	33,103	1734	33,103	1992	33,102
1224	35,060	1482	33,103	1740	33,103	1998	33,102
1230	35,060	1488	33,103	1746	33,103	2004	33,102
1236	35,060	1494	33,103	1752	33,103	2010	33,102
1242	35,060	1500	33,103	1758	33,103	2016	33,102
1248	35,070	1506	33,103	1764	33,103	2022	33,102
1254	35,070	1512	33,103	1770	-33,103	2028	33,102
1260	35,070	1518	33,103	1776	33,103	2034	33,102
1266	35,070	1524	313,103	1782	33,103	2040	33,102
1272	35,075	1530	33,103	1788	33,103	2046	33,102
1278	35,075	1536	33,103	1794	33,103	2052	33,102
1284	35,075	1542	33,103	1800	33,103	2058	33,102
1290	35,075	1548	33,103	1806	33,103	2064	33,102
1296	35,080	1554	33,103	1812	33,103	2070	33,102
1302	35,079	1560	33,103	1818	33,103	2076	33,102
1308	35,079	1566	33,103	1824	33,103	2082	33,102
1314	35,079	1572	33,103	1830	33,103	2088	33,102
1320	35,089	1578	33,103	1836	33,103	2094	33,102
1326	35,089	1584	33,103	1842	33,103	2100	33,102
1332	35,089	1590	33,103	1848	33,103	2106	33,102
1338	35,089	1596	33,103	1854	33,103	2112	33,102
1344	35,094	1602	33,103	1860	33,103	2118	33,102
1350	35,094	1608	33,103	1866	33,103	2124	33,102
1356	35,094	1614	33,103	1872	33,103	2130	33,102
1362	35,094	1620	33,103	1878	33,103	2136	33,102
1368	35,099	1626	33,103	1884	33,103	2142	33,102
1374	35,099	1632	33,103	1890	33,103	2148	33,102
1380	35,099	1638	33,103	1896	33,102	2154	33,102
1386	35,099	1644	33,103	1902	33,102	2160	33,102
1392	35,110	1650	33,103	1908	33,102	2166	33,102

1398	35,110	1656	33,103	1914	33,102	2172	33,090
1404	35,110	1662	33,103	1920	33,102	2178	31,258
1410	35,110	1668	33,103	1926	33,102		
1416	35,115	1674	33,103	1932	33,102		
1422	35,115	1680	33,103	1938	33,102		
1428	35,115	1686	33,103	1944	33,102		
1434	35,115	1692	33,103	1950	33,102		
1440	33,103	1698	33,103	1956	33,102		
1446	33,103	1704	33,103	1962	33,102		
1452	33,103	1710	33,103	1968	33,102		

Table 6.13.-- Hoover Dam probable maximum flood for August

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
0	1,966	300	427,974	600	36,937	900	35,060
6	1,966	306	384,314	606	36,781	906	35,060
12	1,976	312	368,365	612	36,660	912	35,055
is	4,307	318	379,850	618	36,564	918	35,055
24	31,289	324	385,9 85	624	36,488	924	35,055
30	56,720	330	355,191	630	36,413	930	35,055
36	56,454	336	312,499	636	36,338	936	35,055
42	54,023	342	274,336	642	36,264	942	35,055
48	51,765	348	226,906	648	36,200	948	35,055
54	49,695	354	180,016	654	36,135	954	35,055
-60	47,789	36U	145,813	660	36,088	960	35,049
66	46,157	366	121,364	666	36,033	966	35,049
72	47,691	372	106,710	672	35,982	972	35,049
78	60,892	378	99,853	678	35,936	978	35,049
84	90,682	384	94,934	684	35,888	984	35,044
90	153,732	390	90,858	690	35,820	990	35,044
96	188,431	396	87,186	696	35,776	996	35,044
102	188,038	402	83,905	702	35,738	1002	35,044
108	185,004	408	80,865	708	35 701	1008	35,044
114	183,971	414	78,050	714	35,676	1014	35,044
120	184,006	420	75,419	720	35,639	1020	35,044
126	184,118	426	72,334	726	35,603	1026	35,044
132	183,582	432	68,792	732	35,574	1032	35,039
138	182,846	438	65,438	738	35,551	1038	35,039
144	182,383	444	62,396	744	35,513	1044	35,039
150	182,162	450	59,617	750	35,486	1050	35,039
156	182,067	456	57,061	756	35,345	1056	35,039
162	182,022	462	54,655	762	35,135	1062	35,039
168	181,978	468	52,351	768	35,087	1068	35,039
174	181,957	474	50,080	774	35,085	1074	35,039
180	181,940	480	47,917	780	35,085	1080	35,034
186	181,928	486	45,904	786	35,085		

						1086	35,034
192	181,909	492	44,063	792	35,075	1092	35,034
198	181,903	498	42,360	798	35,075	1098	35,034
204	181,898	504	40,831	804	35,075	1104	35,029
210	181,893	510	39,784	810	35,075	1110	35,029
216	181,877	516	39,386	816	35,070	1116	35,029
222	181,873	522	39,138	822	35,070	1122	35,029
228	181,868	528	38,901	828	35,070	1128	35,029
234	181,245	534	38,672	834	35,070	1134	35,029
240	170,201	540	38,463	840	35,065	1140	35,029
246	140,175	546	38,258	846	35,065	1146	35,0219
252	111,795	552	38,072	852	35,065	1152	35,024
258	91,035	558	37,889	858	35,065	1158	35,024
264	77,226	564	37,721	864	35,060	1164	35,024
270	72,279	570	37,569	870	35,060	1170	35,024
276	104,896	576	37,431	876	35,060	1176	35,019
282	1,095,589	582	37,297	882	35,060	1182	35,019
288	597,857	588	37,167	888	35,060	1188	35,019
294	516,538	594	37,050	894	35,060	1194	35,019

Table 6.13.-- Hoover Dam probable maximum flood for August (continued)

Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)	Hour	Flow (ft^3/s)
1200	35,019	1458	33,103	1716	33,102	1974	33,102
1206	35,019	1464	33,103	1722	33,102	1980	33,102
1212	35,019	1470	33,103	1728	33,102	1986	33,102
1218	35,019	1476	33,103	1734	33,102	1992	33,102
1224	35,019	1482	33,103	1740	33,102	1998	33,102
1230	35,019	1488	33,103	1746	33,102	2004	33,102
1236	35,019	1494	33,103	1752	33,102	2010	33,102
1242	35,019	1500	33,103	1758	33,102	2016	33,102
1248	35,024	1506	33,103	1764	33,102	2022	33,102
1254	35,024	1512	33,103	1770	33,102	2028	33,102
1260	35,024	1518	33,103	1776	33,102	2034	33,102
1266	35,024	1524	33,103	1782	33,102	2040	33,102

1272	35,029	1530	33,103	1788	33,102	2046	33,102
1278	35,029	1536	33,103	1794	33,102	2052	33,102
1284	35,029	1542	33,103	1800	33,102	2058	33,102
1290	35,029	1548	33,103	1806	33,102	2064	33,102
1296	35,034	1554	33,103	1812	33,102	2070	33,102
1302	35,034	1560	33,103	1818	33,102	2076	33,102
1308	35,034	1566	33,103	1824	33,102	2082	33,102
1314	35,034	1572	33,103	1830	33,102	12088	33,102
1320	35,039	1578	33,103	1836	33,102	2094	33,102
1326	35,039	1584	33,103	1842	33,102	2100	33,102
1332	35,039	1590	33,103	1848	33,102	2106	33,102
1338	35,039	1596	33,103	1854	33,102	2112	33,102
1344	35,044	1602	33,103	1860	33,102	2118	33,102
1350	35,044	1608	33,103	1866	33,102	2124	33,102
1356	35,044	1614	33,103	1872	33,102	2130	33,102
1362	35,044	1620	33,102	1878	33,102	2136	33,102
1368	35,049	1626	33,102	1884	33,102	2142	33,102
1374	35,049	1632	33,102	1890	33,102	2148	33,102
1380	35,049	1638	33,102	1896	33,102	2154	33,102
1386	35,049	1644	33,102	1902	33,102	2160	33,101
1392	35, ,049	1650	API 102	1908	33, I 102	2166	33,101
1398	35,049	1656	33,102	1914	33,102	2172	33,090
1404	35,049	1662	33,102	1920	33,102	2178	31,258
1410	35,049	1668	33,102	1926	33,102		
1416	35,049	1674	33,102	1932	33,102		
1422	35,049	1680	33,102	1938	33,102		
1428	35,049	1686	33,102	1944	33,102		
1434	35,049	1692	33,102	1950	33,102		
1440	33,103	1698	33,102	1956	33,102		
'1446	33,103	1.704	33,102	1962	33,102		
1452	33,103	1710	33,102	1968	33,102		

The Hoover and Glen Canyon PMFs were routed through Lakes Mead and Powell, respectively, to determine whether or not either dam would be overtopped. The results of the reservoir routings for the August PMFs, which represent the most critical conditions at each dam, are shown on figure 6.9 for Glen Canyon Dam and figure 6.10 for Hoover Dam. Neither facility is overtopped. In fact, Glen Canyon Dam has more that five feet of freeboard remaining below the dam crest, and Hoover Dam still has three feet below the parapet wall. At Hoover Dam, the water surface rose one foot higher than the dam crest elevation.

The PMF reservoir routings used simplified spillway rating curves for both Hoover and Glen Canyon Dams. The spillways were assumed to operate at full capacity, 400,000 and 180,000 ft^3/s at Hoover and Glen Canyon, respectively, as soon as the reservoirs reached uncontrollable levels (elevation 1,226.9 feet at Hoover and elevation 3,700 feet at Glen Canyon). The spillways were allowed to maintain these high discharges for as long as necessary without regard to downstream consequences until the lakes fell below uncontrollable levels. These assumptions were necessary to have a consistent set of routing rules by which all PMF scenarios could be compared. These preliminary routings were used to evaluate the many possible combinations of events available and select the most critical events based on the maximum reservoir elevations.

6.5 PEAK DISCHARGE ENVELOPE CURVE

The envelope curve presented as figure 6.11 is based on peak discharges from all of the gages in the Colorado River basin with drainage areas larger than 100 square miles. A WATSTORE data retrieval was used in developing the information for the curve. The maximum peak flows were plotted along with the corresponding drainage area for the gages. Then the envelope curve was constructed by enclosing the data with a curve. The PMFs for Hoover and Glen Canyon Dams have peak discharges which are more than 100 and 50 percent larger, respectively, than the flows indicated by the curve for similar sized watersheds.

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