TECHNICAL SERVICE CENTER
DENVER, COLORADO

Glen Canyon Dam
Arizona

DAM FAILURE INUNDATION STUDY

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U.S. Department of the Interior
Bureau of Reclamation

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DATE	PEER REVIEWER(S)	CODE
10-14-98	WAYNE J. GRAHAM Wayne J Graham	D-8540

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MEMORANDUM

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TO: Regional Director, Salt Lake City, UT
Attention: UC-255 (Madsen)
(w/attachment - 5 copies)

Regional Director, Boulder City, NV
Attention: BCOO-4840 (Bayne)
(w/attachment)

Chief, Dam Safety Office
Attention: D-6600 (Noel)
(w/attachment)

FROM: Stephen E. Latham, Civil Engineer
Technical Service Center
Sedimentation & River Hydraulics Group

SUBJECT: Dam Failure Inundation Study, Glen Canyon Dam, Arizona

Attached is the Dam Failure Inundation Study for Glen Canyon Dam, dated July 1998. This study describes the flooding that would result along the Colorado River from Glen Canyon Dam to Lake Mead and Hoover Dam. Failure scenarios included a sunny-day failure and an overtopping failure. Inundation maps were not prepared for the canyon areas downstream of Glen Canyon Dam because it was felt they would not visually portray the severity of flooding in the deep, narrow canyon areas. However, inundation maps for the more populated areas around Lake Mead have been prepared and are included with the study.

Information in this study can be used in Reclamation's emergency action plan for Glen Canyon, and as an aid to help local authorities develop warning and evacuation plans.

This document was peer reviewed by Wayne Graham. If you have questions concerning this study please contact Wayne Graham at (303) 445-2553, or me at (303) 445-2519.

/s/ Stephen E. Latham

Attachment

cc: Director, Operations
Attention: W-6340 (Brynda) (w/o attachment)
Chief, Dam Safety Office
Attention: D-6600 (Rocklin) (w/o attachment)

bc: D-5500 (Kinney)
(w/o attachment)
D-8010 (Hughes)
D-8470 (Bortz)
D-8540 (Files, Graham, Latham)
(w/attachment to each)

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[glencany.msl]

Dam Failure Inundation Study
Glen Canyon Dam AZ

GLEN CANYON DAM, ARIZONA
DAM FAILURE INUNDATION STUDY

Purpose of Study

The purpose of this study is to estimate the magnitude of flooding that would result along the Colorado River from Lake Powell to Hoover Dam due to the failure of Glen Canyon Dam. This study was requested by the Upper Colorado Regional Office of the Bureau of Reclamation (Reclamation) in August 1995, and is pursuant to the policy established by the Commissioner of Reclamation in his memorandum dated February 27, 1995 [1]. This information can be used in Reclamation's emergency action plan for Glen Canyon Dam, and as a reference in preparing inundation maps for areas downstream of the dam. It can also be used to help local authorities develop warning and evacuation plans.

Background Information

Glen Canyon Dam, completed in 1964, is located on the Colorado River in northern Arizona, approximately 15 river miles upstream from Lee's Ferry and 12 river miles downstream from the Arizona-Utah State line (see Figure 1). The dam is a constant-radius concrete arch structure with fillets (see Figures 2 and 3). Structural data, appurtenant capacities, and reservoir elevation and capacity data are tabulated on Figure 4.

Glen Canyon Dam is a key feature of the Colorado River Storage Project and contributes to the longtime regulatory storage needed to permit the upper basin states to use their share of water apportioned under the terms of the 1922 Colorado River Compact. In addition to regulatory storage, the dam provides for power generation, improved sediment and flood control, fish and wildlife conservation, and recreational benefits.

Inundation maps showing the areas downstream of Glen Canyon Dam that would be affected by failure of the dam have never been prepared. This study is the first of its kind to be undertaken for Glen Canyon by Reclamation. The study extended from Glen Canyon Dam, through the Grand Canyon, onto Lake Mead, and ended at Hoover Dam. The study did not extend beyond Hoover Dam, but estimates of discharges downstream from Hoover are presented.

Flood Scenarios Evaluated

The following two scenarios were considered to cover the range of events that could cause failure of Glen Canyon Dam. Both scenarios are extremely unlikely and represent worst-case scenarios that result in the largest uncontrolled releases of the reservoir. Various assumptions were made to help test the sensitivity of results to those assumptions.

(1) **Dam failure caused by foundation failure or other defect (Sunny-Day Failure).** This scenario includes a 100-year base snowmelt inflow to Lake Powell.

(2) **Dam failure caused by overtopping brought about by the overtopping failure of Flaming Gorge Dam.** This scenario involves an extremely large flood inflow to Lake Powell.

Description of Hydrologic Events

These paragraphs describe the hydrologic events for Scenario 2 above. The current probable maximum flood (PMF) for Glen Canyon Dam was developed in 1989 [2]. Results of routing the 1989 PMF indicate that the dam is not overtopped and 8 feet to 12.5 feet of freeboard is provided depending upon outflow restrictions. However, the flood could overtop Glen Canyon Dam brought about by the overtopping failure of Flaming Gorge Dam, about 580 miles upstream.

Current flood routings indicate that Flaming Gorge Dam will not be overtopped during its PMF. However, if conditions were such that the spillways were blocked and/or inoperable during the PMF, Flaming Gorge Dam could be overtopped [3]. For this study, it was assumed the dam would fail during overtopping. (This is very unlikely in reality.) Should this overtopping failure of Flaming Gorge occur with the starting reservoir water surface at normal capacity, a combined outflow of 5,320,300 acre-feet would result. With Lake Powell at its normal capacity (water surfaces at elevation 3700), this combined outflow would exceed the available surcharge storage capacity at Glen Canyon (2,498,560 acre-feet) [3].

Dam Failure Modeling and Assumptions

The flood forecasting computer program, BOSS DAMBRK (DAMBRK) [4], was used to help prepare this study. Within the program, computation option 13 was selected as the option that would best model the Grand Canyon environment. It also gave more conservative results. Option 13 uses the simultaneous solution method for routing a flood through a single dam (storage or level pool routing upstream of the structure and dynamic routing downstream of the structure).

Reservoir surface area data obtained from area-capacity curves in the 1986 Lake Powell Survey [5] were used as input for the computer model to describe the elevation/storage relationship at Lake Powell. Surface area data for water surface elevations above 3700 feet were obtained by extrapolating the area curve in reference [5].

For the Sunny-Day Failure, the initial reservoir water surface for the computer model was assumed to be elevation 3711 (design maximum water surface). The outflow discharge curve for the computer model was set up to simulate expected spillway operations for the reservoir at this level according to the Standing Operating Procedures (SOP) [6]. Outflows through the river outlet works were combined with an outflow through the powerplant and entered in the model as turbine discharge. Though this created an overlap error of the spillway and outlet works discharge (SOP states that these are to be operated in tandems to comply with total discharge

restrictions downstream), the short breach time and magnitude of breach outflows made this error negligible.

For the Sunny-Day Failure, it was assumed that Lake Powell had experienced inflow from a 100-year base snowmelt year, this being the reason for the high reservoir level, elevation 3711 (4 feet below the dam crest). This assumption was based on historical end-of-month (EOM) reservoir level for June and July in both years 1983 and 1984 when flood surcharges took the reservoir level above elevation 3700 (top of active conservation). (EOM water surface elevations were 3707.1 for June and 3707.4 for July in 1983, and 3701.3 for June and 3702.7 for July in 1984.) The year 1984 is considered a high-runoff year [5,7], having experienced a 100-year inflow. This type of snowmelt inflow hydrograph normally peaks during late May or early June [7]. Therefore, part of the trailing leg of the 100-year base snowmelt hydrograph was entered into the model for this scenario.

For the Overtopping Failure, the initial reservoir water surface for the computer model was assumed to be elevation 3700 (top of active conservation). To determine the duration and magnitude of overtopping potential, a flood inflow hydrograph (due to the Flaming Gorge failure) was first estimated. The Dam Failure Inundation Study for Flaming Gorge Dam, January 1990 [8], was used as a reference to help develop this hydrograph. Since that study ended at Green River, Utah (about 130 miles from the upper reaches of Lake Powell), peak discharges were extrapolated downstream to Lake Powell, and an estimated inflow hydrograph was generated using the Flaming Gorge failure volume (5,320,300 acre-feet). Finally, it was assumed that the flood inflow hydrograph arrived at the upper reaches of Lake Powell when the lake water surface was still at elevation 3700. This assumption is conservative because in reality, personnel at Glen Canyon would likely have taken measures to lower Lake Powell upon hearing about the failure of Flaming Gorge (it would take roughly 34 hours for the maximum stage of the flood wave to arrive at the upper reaches of Lake Powell). However, routing the estimated flood inflow hydrograph indicated that Glen Canyon Dam would be overtopped for a duration of about 40 hours, reaching a peak depth of 2.9 feet over the parapet wall. While it is unlikely this overtopping flow would cause the dam to fail, for the purposes of evaluating this scenario, failure was assumed.

Outflow assumptions prior to the Overtopping Failure were as follows. As previously mentioned, measures would likely have been taken at Glen Canyon Dam to lower Lake Powell, probably by opening the spillways 2 to 3 hours after notification of the Flaming Gorge failure. However, for this study it was conservatively assumed that release thus far (30-plus hours) would have been according to SOP guidelines (25,000 to 35,000 ft^3/sec through the river outlet works and powerplant combined) to allow time for evacuation of the canyon downstream of Glen Canyon Dam. Then, upon arrival of the flood wave at the upper reaches of Lake Powell, it was assumed that the spillway gates would be opened uniformly from zero discharge at water surface elevation 3700 to the normal maximum discharge of 238,000 ft^3/sec by water surface elevation 3705 [9]. For water surface elevations above 3711, a straight-line extrapolation of the spillway rating curve [9] was used.

For the Overtopping Failure, Glen Canyon Dam was assumed to commence failure when Lake Powell reached water surface elevation 3721.9, or 2.9 feet over the top of the parapet wall on the crest of the dam. Routing calculations showed this point in time to be 54 hours from the time when the estimated flood inflow hydrograph arrived at the upper reaches of Lake Powell. For the computer model of the dam breach, this was chosen as time zero. Outflows from the dam right now would be about 400,000 ft^3/sec through the spillways, river outlet works, and powerplant combined, and about 23,000 ft^3/sec over the parapet wall.

Three sets of Manning's n values were used in each failure scenario for the canyon between Glen Canyon Dam and Lake Mead to test the sensitivity of flood arrival times and flood depths to roughness coefficient. These included a run with "low," or "smooth" values (generally n = 0.06), a run with "high," or "rough" values (generally n = 0.10), and a run using values that varied down the channel (from 0.055 to 0.12). This third set of varying n values was based on calibrating the model to match stage-discharge rating curves developed in 1992 at Reclamation's Technical Service Center for various reaches of the Grand Canyon from Lees Ferry to Diamond Creek. These curves were developed as part of the work for the final environmental impact statement for the operation of Glen Canyon Dam [10] for flood discharges in the Colorado River up to 45,000 ft^3/sec. Generally, calibrating the computer model's sections to match the 1992 rating curves by adjusting only the Manning's n value was successful to ± 5 feet, except five locations (interpolated sections in the model) which were within ± 10 feet. Although ± 10 feet seems like a rather large error range, for the magnitude of discharges and depths determined in this study, it was considered practically negligible.

Breach parameters assumed in the computer modeling were the same for both failure scenarios. Initially, a breach formation time of 10 minutes was assumed for this concrete arch dam. This short failure time is in line with historical observations of other concrete arch and gravity dams that have failed by collapse, overturning, sliding away, or failure of abutment or foundation material. However, the computer model had trouble with such a short breach formation time and nonconvergence problems were encountered. Time restraints for this study did not allow for an investigation to rectify this problem. Therefore, the following breach formation times were used. These times were the minimum allowed by the DAMBRK model to complete a successful routing.

Sunny-Day Failure:

Low Manning's n run	Breach Formation 1.9 hours
Calibrated Manning's n run	Breach Formation 1.9 hours
High Manning's n run	Breach Formation 0.26 hours

Overtopping Failure:

Low Manning's n run	Breach Formation 1.6 hours
Calibrated Manning's n run	Breach Formation 1.3 hours
High Manning's n run	Breach Formation 0.50 hours

Other Breach Parameters:

Breach side slope = zero horizontal to 1 vertical
Breach bottom elevation = 3128 feet
Breach base width = 430 feet

Cross section geometry used in the model was obtained from U.S. Geological Survey (USGS) topographic maps (7.5 minute quadrangles) displaying 40-foot contour intervals [11]. Some 49 cross sections were used in the DAMBRK computer modeling. See Figure 5 for a map showing the approximate locations of the cross sections. Channel bottom width and invert elevation for each cross section was estimated by assuming the USGS maps reflect a flow of 15,000 ft^3/sec and assuming a trapezoidal section with ½ horizontal to 1 vertical side slopes. Data from a 1992-USGS collection of bound tables regarding characteristics of morphologically similar reaches were used to help estimate depths of flow for each section [12]. Depending on the section, depths for a flow of 15,000 ft^3/sec ranged from 8 feet to 34 feet.

Stationing for the computer model was based on Lees Ferry being river mile zero. Cross sections downstream from Lees Ferry were referenced as positive miles while everything upstream was referenced as negative miles. This convention is currently the same one used by recreational boaters and rafters who navigate the canyon downstream from Lees Ferry. Glen Canyon Dam is 15.5 miles upstream from Lees Ferry. Therefore, its location was designated as river mile negative 15.5 (-15.5). (Within the model itself cross sections were numbered with Lees Ferry as mile 1000.0. This was because DAMBRK does not recognize negative stationing.)

For cross sections downstream of river mile 238, special consideration was required to determine current invert elevations. The Colorado River enters the upstream reaches of Lake Mead near river mile 238. Currently available USGS topographic maps for this reach reflect aerial photography performed in 1966, 1967, and 1970. The highest Lake Mead water surface elevation of record for these years was 1153.65 feet (January 1970) [13]. However, to use this elevation as a reference for estimating a channel invert does not reflect current conditions. Sediments have accumulated in this reach since 1964 and have raised the channel invert considerably [14,15]. Based on discussions with Reclamation personnel [15], a channel invert 5 feet below the September 1993 EOM Lake Mead water surface elevation of 1189.15, or 1184 rounded to the nearest foot, was assumed at river mile 238.1. Approximations of the channel invert for sections downstream from river mile 238.1 to South American Point (about river mile 286) were subsequently made based on estimated 1998 growth projections of the Colorado River sediment delta (Figure 5-3 in reference [17]) in Lake Mead. It was noted that the delta sediments are dynamic depending on the water level in Lake Mead. So, the approximate invert elevations for this reach were considered reasonable "ballpark" values.

The weir coefficient for modeling overtopping of Glen Canyon Dam was assumed to be 2.9. The effective crest length used for overtopping was the full crest length of the dam, 1560 feet.

Volume losses due to lateral outflows (into side canyons and tributaries) were assumed to be negligible for the computer modeling. Although these losses could affect flood wave travel times significantly, this level of detail for the model was beyond the scope of this study. In addition, these volume losses would be very small compared with the volume of water released during the dam failure.

The arrival time of the leading edge of the flood wave at any cross section was assumed to be that point in time when the flow depth hydrograph begins to rise sharply. This reflects the actual point in time at which flooding due to dam failure begins.

The flood wave due to dam failure was routed by DAMBRK from Glen Canyon Dam (river mile - 15.5) to the upstream reaches of Lake Mead (about river mile 238). Near this point the Colorado River deposits its sediment load and the channel invert profile makes an abrupt change to a shallower slope. From river mile 238 to just upstream of South American Point (about river mile 286), the channel remains shallow and becomes wider. This required a separate run of DAMBRK for routing the flood hydrograph at model section 1230.9 (river mile 230.9) to determine flood crest depths and travel times from river mile 238 to South American Point (i.e., the upper reaches of Lake Mead). Only the flood hydrograph from the Overtopping Failure was routed here. Beyond South American Point (about river mile 286), the lake bottom drops off sharply.

The flood hydrograph at South American Point (about river mile 286) was then considered the flood to be routed through Lake Mead and Hoover Dam. This was accomplished using Reclamation program FLROUTM.EXE [16] which employs storage or level pool reservoir routing. Assumptions for this routing through Hoover Dam were as follows.

Lake Mead capacity data were obtained from area-capacity curves in the 1963-64 Lake Mead Survey [17]. These were used as input for FLROUTM.EXE to describe the elevation/storage relationship at Lake Mead. Capacity data for water surface elevations above 1230 feet were obtained by extrapolating the capacity curve in reference [17].

Two different initial water surface elevations were assumed for Lake Mead at the start of routing the flood from the Glen Canyon Overtopping Failure. These elevations were supplied by Reclamation's Boulder Canyon Operations Office as Lake Mead target elevations for each year. These were elevation 1219.61 for July and elevation 1214.50 for December. Although initial conditions from the Glen Canyon Overtopping Failure indicate flows of 300,000 ft^3/sec to 400,000 ft^3/sec down the canyon and into Lake Mead before Glen Canyon fails, it was assumed that for water surface elevations 1214 to 1217.5, Hoover would be releasing only 65,000 ft^3/sec (through the river outlet works and/or powerplant) to allow, primarily, for warning and evacuation time downstream of Hoover Dam. For water surface elevations above 1217.5, it was assumed that the spillway gates would be opened uniformly from zero discharge at water surface elevation 1217.5 to the normal maximum discharge of 164,000 ft^3/sec by water surface elevation 1220 [18]. Discharge through each spillway top out at 192,500 ft^3/sec at water surface

elevation 1235. Maximum discharge through the river outlet works is about 73,000 ft^3/sec above water surface 1220 since recent installation of new jet-flow gates. Maximum discharge through the powerplant above water surface 1220 is 27,600 ft^3/sec [19].

Assuming Hoover Dam does not fail, the magnitude and duration of overtopping were estimated. This routing also provided an estimate of the discharges to be expected over Hoover Dam from a flood of this magnitude. See the following section for these values.

Study Results

As for flood crest depths, the results of Glen Canyon Dam failing due to a Sunny-Day Failure or an Overtopping Failure were the same for practical purposes. For the Sunny-Day Failure, maximum water depths from Glen Canyon Dam (river mile -15.5) to the upstream reaches of Lake Mead (about river mile 238) ranged from 310 feet to 570 feet above the water surface shown on the USGS topographic maps depending on the cross section. For the Overtopping Failure, maximum water depths ranged from 320 feet to 580 feet depending on the cross section. These depth ranges were for the computer runs using the calibrated roughness values that varied down the canyon from 0.055 to 0.12 depending on the cross section.

For the run with "smooth" roughness values (generally n = 0.06), depths ranged from 320 feet to 520 feet for the Sunny-Day Failure, and 330 feet to 530 feet for the Overtopping Failure, depending on the cross section. For the run with "rough" values (generally n = 0.10), depths ranged from 350 feet to 540 feet for the Sunny-Day Failure, and 360 feet to 550 feet for the Overtopping Failure depending on the cross section.

Manning's n roughness did not affect flood crest depths. In general, for either failure mode, for any particular cross section, flood crest depths varied ± 34 feet depending on the roughness values selected. This variance was 7 percent or less of the flood crest depth at any cross section.

Flood arrival times were more sensitive to Manning's n roughness. Near Phantom Ranch (river mile 87), the arrival time of the leading edge of the flood wave increased by 15 percent when higher roughness values were assumed. Near Diamond Creek (river mile 225), the arrival time of the leading edge of the flood wave increased by 41 percent.

Near Lees Ferry (river mile zero) and Navajo Bridge (about river mile 4.7), the arrival time of the peak flood stage increased by 10 percent when higher roughness values were assumed. Near Phantom Ranch (river mile 87), the arrival time of the peak flood stage increased by 38 percent, and near Diamond Creek (river mile 225), the arrival time of the peak flood stage increased by almost 50 percent when higher roughness values were assumed. These increases were in accord with expected results.

Evaluation of results indicates that the leading edge of the flood wave due to dam failure would likely reach Diamond Creek (river mile 225) in 10 hours to 12 hours for either failure scenario.

This takes into account the fact that the DAMBRK model would only allow a minimum of 1.9 hours and 1.3 hours breach formation time for the Sunny-Day Failure and Overtopping Failure, respectively. This converts to a flood wave travel rate of 20 miles per hour (mph) to 25 mph. Arrival of maximum flood stage would occur about 20 hours to 22 hours after dam failure.

See Table 1 for a summary of estimated ranges of maximum depths, flood arrival times, and peak discharges at selected locations.

Table 1

Location (River Miles from Lees Ferry)	Summary of Data Ranges [A]				
	Water surface elev. [B]	Max. depth above water surface [B]	Arrival time of leading edge [C]	Arrival time of peak stage	Maximum discharge
-15.5 Glen Canyon Dam	3700 ft	11.0 - 21.9 ft [D]	0 hr	0 hr	18.0 - 19.2 (million cfs)
0.0 Lees Ferry	3115.5 ft	480 - 520 ft	0.6 - 0.7 hr	5.5 - 6.5 hr	10.0 - 14.7 (million cfs)
4.7 Navajo Bridge	3094.7 ft	470 - 530 ft	0.7 - 0.8 hr	5.6 - 6.7 hr	7.8 - 12.2 (million cfs)
87.0 Phantom Ranch	2428.5 ft	400 - 480 ft	4.0 - 5.5 hr	10 - 14 hr	7.0 - 11.4 (million cfs)
135.3 Granite Narrows	1947.5 ft	440 - 480 ft	6.5 - 8.5 hr	13 - 19 hr	6.9 - 11.2 (million cfs)
178.0 Lava Pinnacle	1680 ft	360 - 430 ft	8.0 - 11.5 hr	15 - 23 hr	6.7 - 11.0 (million cfs)
225.0 Diamond Creek	1327 ft	470 - 540 ft	10.5 - 15.0 hr	18 - 27 hr	6.5 - 10.7 (million cfs)
281.5 [E] End of Pearce Basin	1181 ft [F]	246 ft [G]	14.5 hr	20 hr	8.7 (million cfs)

Footnotes:
[A] Ranges cover extremes for both Sunny-Day Failure and Overtopping Failure plus extremes for Manning's n roughness assumptions.
[B] Water surfaces as shown on USGS 7.5 minute quadrangle maps.
[C] It should be noted that for the Overtopping Failure, major flooding will already be occurring prior to the arrival of the leading edge of the flood wave caused by dam failure.
[D] Depths at this section (the upstream face of the dam) are referenced above Lake Powell normal capacity water surface elevation, 3700 feet.
[E] Values for this location are only for flood from an Overtopping Failure.
[F] "Ballpark" estimate of channel invert for this study (due to accumulated sediments since 1964).
[G] Depth above estimated channel invert.

Routing the flood hydrograph at model section 1230.9 (river mile 230.9) through the upper reaches of Lake Mead resulted in progressive maximum water depths of 507 feet at river mile 238, to 246 feet at river mile 281.5 (approximate the end of Pearce Basin), to 252 feet at river mile 286.2 (South American Point) for the Overtopping Failure. These depths are referenced above the estimated invert of the channel in this reach because of the accumulated sediments that have occurred since 1964 [14, 15]. Only the flood hydrograph from the Overtopping Failure was routed here.

The leading edge of the Overtopping Failure flood wave would likely reach South American Point (about river mile 286) in 13 hours to 15 hours after dam failure. This equates to a flood travel rate in the upper reaches of Lake Mead of 17 mph to 18 mph. Arrival of maximum flood stage would occur about 19 hours to 20 hours after dam failure.

The reason for the maximum flood stage times at South American Point (about river mile 286) being less (i.e., 1 hour to 2 hours sooner) than at Diamond Creek (river mile 225) is likely due to a combination of at least two things. These include: (1) a much shallower channel slope in the upper reaches of Lake Mead, and (2) the fact that the canyon cross section at South American Point is suddenly very narrow and creates a constriction producing some backwater effects. This is in accord with the rise in water surface indicated by the model from river mile 281.5 (approximate end of Pearce Basin) to river mile 285.5 (near South American Point).

As mentioned earlier, the flood hydrograph at South American Point (about river mile 286) due to the Overtopping Failure of Glen Canyon was routed through Lake Mead and Hoover Dam. The results were practically identical for both initial water surface elevations assumed for Lake Mead. These were elevation 1219.61 (target for July) and 1214.50 (target for December). Assuming Hoover Dam does not fail, overtopping would begin about 23 to 24 hours after the failure of Glen Canyon, continue for about 258 hours (10¾ days), and reach a peak depth of about 68 feet over the parapet wall on the dam crest at hour 74. This depth corresponds to a maximum water surface elevation in Lake Mead of 1304 feet. Maximum discharges would be about 485,600 ft^3/sec through the river outlet works, powerplant, and spillways, and 2.02 million ft^3/sec over the dam crest. This makes a total discharge immediately downstream from Hoover Dam of over 2.5 million ft^3/sec.

Discussion of Results

The failure of Glen Canyon Dam due to a Sunny-Day Failure or an Overtopping Failure would produce catastrophic flooding with unprecedented flood depths and discharges all the way to Lake Mead and Hoover Dam. Even if Hoover Dam did not fail, there would be unprecedented flooding downstream of Lake Mead as well.

Though the magnitude of flood depths and discharges would be about the same for either the Sunny-Day Failure or the Overtopping Failure, it should be noted that prior to an Overtopping Failure, major flooding would already be occurring downstream from Glen Canyon Dam. These

magnitudes would be about 50-foot to over 100-foot depths and 300,000 ft^3/sec to over 400,000 ft^3/sec. This is based on the assumption that the river outlet works, powerplant, and spillways would have already been operating for some time trying to prevent the dam from being overtopped.

Obviously any type of structure less than 400 feet to 500 feet above the Colorado River between Glen Canyon Dam and Lake Mead as shown on USGS topographic maps would be completely inundated and destroyed by the flood from either type of failure. Even Navajo Bridge (near river mile 4.7), which is about 400 feet above the Colorado River, could be damaged or destroyed. Results indicate depths of around 500 feet at this location. Flooding of this magnitude anywhere in the canyon would be very severe and lethal. Anyone still on the river at the time of this flooding would have to climb the equivalent of a 40-story building, at a minimum, to have any hope of surviving.

The study indicated that the travel rate for the leading edge of the flood wave was estimated to be 20 mph to 25 mph. Although there have been no dam failures of this magnitude observed historically, these travel rates may be reasonable for this huge a failure outflow. Some flood wave travel times from other dam failures with similar downstream reaches include:

(1) St. Francis Dam, California, failed on March 12, 1928. Flows traveled 18 mph in the first 1.5 miles downstream from the dam. Peak discharge unknown.
(2) Hell Hole Dam, California, failed on December 23, 1964. Flows traveled 14 mph through the narrow and uninhabited rock canyon 56 miles to Folsom Reservoir. Peak discharge was estimated to be 260,000 ft^3/sec. Volume released was 24,800 acre-feet.
(3) Teton Dam, Idaho, failed on June 5, 1976. Flows traveled 19 mph in the narrow canyon for 2.5 miles, and averaged 16 mph for the first 8.8 miles downstream from the dam. Peak discharge was estimated to be 2,300,000 ft^3/sec. Volume released was 251,700 acre-feet.
(4) Little Deer Creek Dam, Utah, failed on June 16, 1963. Flows traveled 18.9 mph in the first 2.2 miles downstream from the dam. Peak discharge was estimated to be 47,000 ft^3/sec. Volume released was 1000 acre-feet.

The study indicated that flood depths in the upper reaches of Lake Mead would progress from 507 feet at river mile 238, to 246 feet at river mile 281.5 (approximate end of Pearce Basin), to 252 feet at river mile 286.2 (South American Point) for the Overtopping Failure. These depths were referenced from the estimated channel invert due to accumulated delta sediments that were not reflected on 28- to 30-year-old USGS topographic maps. It is very possible that these recently deposited sediments would be scoured by a dam-failure flood of this magnitude to the extent of altering the behavior of the flood wave to something completely different from this study assumed. Flood depths might increase to a great degree, especially since South American Point could become a major bottleneck for pushing these sediments through. More study would be required to confirm this possibility.

Mapping of inundated areas in the Grand Canyon between Glen Canyon Dam and Lake Mead was not prepared. Because of the canyon areas being so deep and narrow, any inundation mapping

would not effectively show the severity of the flooding. The inundation boundary for a flooding depth of 450 feet would not appear much different from the boundary for a flooding depth of 100 feet. Additionally, there are few permanently inhabited structures down through the canyon areas. Therefore, flooding results in the canyon areas between Glen Canyon and Lake Mead are presented as described in the previous section, Study Results, and in Table 1.

However, mapping of some more populated areas around Lake Mead that would be inundated have been prepared. These areas generally include marinas, campgrounds, and other concentrations of population and activity. Water depths would be around 84 feet above the July target elevation of 1219.61 feet for Lake Mead.

The results presented in this report are based on a number of gross assumptions how the floods from the failure scenarios develop and how Glen Canyon Dam and Hoover Dam might be operated in such extreme conditions. These assumptions were intended to produce worst-case scenarios. Greater precision of the data ranges presented in Table 1 would require consideration of volume losses due to lateral outflows (into side canyons and tributaries), consideration of mud/sediment/debris-type flows especially in the upper reaches of Lake Mead, further refinement of roughness coefficients for the canyon, further consideration of actual emergency operations at both dam facilities, and using dynamic routing analyses of the flood wave through Lake Powell and Lake Mead since they are both long and sinuous with several large tributary arms. It is possible that these factors and others could lengthen flood wave travel times and attenuate maximum flood depths, especially as the flood wave approaches Lake Mead. However, the results of this study are considered sufficient to estimate the magnitude of flooding resulting from the hypothetical failure of Glen Canyon Dam.

REFERENCES

[1] Memorandum to: Director, Policy and External Affairs; Director, Operations; Director, Program Analysis Office; Regional Director, PN, MP, LC, UC, GP; from Commissioner, Subject: "Policy for Establishing an Emergency Management Program at Reclamation Facilities," Bureau of Reclamation, Washington, D.C., February 27, 1995.

[2] Memorandum to Chief, Civil Engineering Division, Attention: D-3100; from Manager, Planning Services Staff, Subject: "Transmittal of Final Probable Maximum Flood Hydrographs for Hoover Dam and Glen Canyon Dam," August 11, 1989.

[3] Technical Memorandum No. GC-8130-1, Subject: "Preliminary Evaluation of the Effects at Glen Canyon Dam Caused by the Failure of Upstream Dams," Glen Canyon Dam, Colorado River Storage Project, Upper Colorado Region, U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado, January 21, 1998.

[4] BOSS DAMBRK™ Flood Forcasting Program, Version 3.00, Copyright 1988-94, Boss Corporation, 6612 Mineral Point Road, Madison, Wisconsin, 53705.

[5] 1986 Lake Powell Survey, REC-ERC-88-6, by Ronald L. Ferrari, Surface Water Branch, Earth Sciences Division, U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado, December 1988.

[6] Standing Operating Procedures for Glen Canyon Dam and Reservoir, Arizona, Colorado River Storage Project, Upper Colorado Region, U.S. Bureau of Reclamation, Salt Lake City, Utah, May 1993.

[7] Antecedent Flood Analysis, Section 4.0, "Colorado River Basin, Probable Maximum Floods for Hoover and Glen Canyon Dams," Flood Hydrology Group, U.S. Bureau of Reclamation, Denver, Colorado, September 1990.

[8] Dam Failure Inundation Study, Flaming Gorge Dam, Colorado River Storage Project, Sedimentation Section, Surface Water Branch, Earth Sciences Division, U.S. Bureau of Reclamation, Denver, Colorado, January 1990.

[9] Drawing No. 557-D-1386, Spillway Discharge Curves for One 40' X 52.5' Radial Gate, Glen Canyon Dam, Colorado River Storage Project, Bureau of Reclamation, Denver, Colorado, May 2, 1961.

[10] Final Environmental Impact Statement, Operation of Glen Canyon Dam, Colorado River Storage Project, Bureau of Reclamation, U.S. Department of the Interior, March 1995.

[11] Arizona 7.5 Minute Series (Topographic) Maps: Page, 1985; Ferry Swale, 1985; Lees Ferry, 1985; Navajo Bridge, 1985; Bitter Springs, 1985; Emmett Wash, 1985; North Canyon Point, 1985; Tatahatso Point, 1988; Buffalo Ranch, 1988; Point Imperial, 1988; Nankoweap Mesa, 1988; Cape Solitude, 1988; Desert View, 1988; Cape Royal, 1988; Phantom Ranch, 1988; Grand Canyon, 1988; Shiva Temple, 1988; Havasupai Point, 1988; Explorers Monument, 1988; Topocoba Hill, 1988; Fossil Bay, 1988; Powell Plateau, 1988; Tapeats Amphitheater, 1988; Fishtail Mesa, 1988; Kanab Point, 1988; Havasu Falls, 1988; S B Point, 1988; Fern Glen Canyon, 1988; Gateway Rapids, 1988; Vulcans Throne, 1967; Whitmore Rapids, 1967; Vulcans Throne SW, 1967; Whitmore Point SE, 1967; Granite Park, 1967; Diamond Peak, 1967; Travertine Rapids, 1967; Peach Springs Canyon, 1967; Separation Canyon, 1967; Spencer Canyon, 1967; Devils Slide Rapids, 1967; Quartermaster Canyon, 1968; Bat Cave, 1971; Columbine Falls, 1971; Snap Canyon West, 1971; Iceberg Canyon, 1983; United States Geological Survey, Department of the Interior.

[12] Bound Tables of *Morphologically Similar Reaches* for the Colorado River from River Mile Zero to River Mile 225.0, U.S. Geological Survey, Boulder, Colorado, received by Tim Randle at the Technical Service Center, Denver, Colorado on February 20, 1992.

[13] Historical EOM Lake Mead Elevations, Lower Colorado Regional Office Website: http://www.lc.usbr.gov, U.S. Bureau of Reclamation, April 1998.

[14] May 7, 1998 discussions via telephone with Mark Gonzales, Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, regarding findings of a preliminary survey performed in 1995-96 to assess accumulation of sediments in the upper reaches of Lake Mead.

[15] May 7, 1998 discussions with Ron Ferrari and Tim Randle, Sedimentation and River Hydraulics Group, Technical Service Center, Bureau of Reclamation, Denver, Colorado, regarding their observations on recent (September 1983 and September 1993) boat trips on the Colorado River, especially in the upper reaches of Lake Mead.

[16] FLROUT, Flood Routing for Dams, Version 3.00, Multiple Dam, Waterways and Concrete Dams Group, Technical Services Center, U.S. Bureau of Reclamation, Denver, Colorado, May 1995.

[17] The 1963-64 Lake Mead Survey, REC-OCE-70-21, by J.M. Lara, Office of Chief Engineer, Denver, Colorado, and J.I. Sanders, Region 3 Office, Boulder City, Nevada, U.S. Bureau of Reclamation, August 1970.

[18] Hydraulic Model Study Results, Hoover Dam Tunnel Spillways, PAP-465, by Kathleen L. Houston (Frizell), Hydraulics Branch, U.S. Bureau of Reclamation, Denver, Colorado, July 24, 1984.

[19] Project Data Book, Water and Power Resources Service, U.S. Department of the Interior, 1981.

DIMENSIONS AND APPURTENANT CAPACITIES

Structural Height of Dam:	710 feet
Hydraulic Height of Dam:	583 feet
Crest Length of Dam:	1560 feet
Top Width of Dam: Note: A 35-foot-wide service road on the crest provides access across the dam and to appurtenances.	25 feet
Crest Elevation of Dam:	3715.0 feet
Top of Parapet Wall:	3719.0 feet

Spillways: A separate 41-foot-diameter concrete-lined tunnel in each abutment, each controlled by two 40- by 52.5-foot radial gates.

Each Spillway Crest Elevation:	3848.0 feet
Elevation at Top of Gates:	3700.0 feet
Combined Spillway Capacity at Maximum Water Surface, Elevation 3711 feet:	276,000 ft^3/sec

River Outlet Works: Four 96-inch-diameter steel pipes, each controlled by one 96-inch ring-follower gate and one 96-inch hollow-jet valve.

Capacity of all River Outlets:	15,000 ft^3/sec

Powerplant: Eight 15-foot-diameter steel penstocks, each controlled by one 13.96- by 22.45-foot fixed-wheel gate.

Maximum Discharge through Powerplant:	28,640 ft^3/sec

RESERVOIR ELEVATIONS AND CAPACITIES

Note: Capacities from 1986 Lake Powell Survey

3711 feet (Design Maximum Water Surface): (Extrapolated)	28,230,000 ac-ft
3700 feet (Top of Active Conservation Pool)	26,210,000 ac-ft
3490 feet (Top of Inactive Storage)	5,905,000 ac-ft
3370 feet (Top of Dead Pool)	1,906,000 ac-ft
3132 feet (Streambed at Dam Axis)	0 ac-ft

Note: For additional details, see Glen Canyon Dam Standing Operating Procedures.

FIGURE 4