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# Hydrology Analysis of the Colorado River Floods of 1983

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**Abstract:** Despite an extensive system of river regulation works, the mainstem of the Colorado River in 1983 experienced the highest flows on record, resulting in severe flood damage. The high flows were due to an abnormally late season mountain snow accumulation, an accelerated snowpack ablation, and high initial reservoir levels. Forecasts of April–July inflow to Lake Powell, the major Upper Basin reservoir, nearly doubled from early May to late June.

The report evaluates the efficacy of runoff and inflow prediction methodologies utilized to formulate reservoir operational responses during the winter and spring of 1983. Given the restrictions inherent in the forecasting network, the reservoir release schedule followed during the period by the US Bureau of Reclamation (USBR) is then reviewed. Two alternative reservoir release schedules are also presented, and their hypothetical impacts on flooding assessed. In light of the 1983 flooding, recommendations are made to increase the reliability of flood predictions for Colorado River reservoirs and to reduce the extent of future damage to and destabilization of the biological and physical resources of Grand Canyon National Park.

A brief epilogue provides an update on the evolution of the Colorado River reservoir operations policy. The new policies helped to attenuate 1984 peak reservoir discharges, even though the 1984 total runoff exceeded that of 1983.

## Introduction

The Colorado River Basin is one of the most regulated river systems in the world (Fig 1). In all but the wettest years all of its water is stored or diverted and normally not a drop reaches the River's end at the Gulf of California. The current network of dams and diversion structures regulates the highly variable basin runoff in accordance with both the apportionments outlined in the Colorado River Compact and Mexican Water Treaties and the priorities, including flood-control and power generation, established by Congressional directives. The regulation of the Colorado River system is complicated by the need to satisfy a multitude of competing demands on its over-appropriated water.

Despite these efforts to tame the Colorado River, highly unusual weather events in the spring and summer of 1983 resulted in unpredictable inflow to the major reservoirs which subsequently required the release of damaging flows from Lake Powell and the Lower Basin reservoirs. These releases had significant impact on the physical and biological resources of the Grand Canyon and human settlements downstream of Hoover Dam. The releases were required because of the lack of flood control reservation in reservoirs whose total storage is equivalent to almost 5 years of normal mainstem runoff. The flood control reservation is managed by the United States Bureau of Reclamation (USBR) in response to periodic reservoir inflow forecasts, and in accordance with flood control regulations and long-range operational criteria. Although the USBR operated the reservoirs within the bounds of these procedures during the 1982–83 water year, the ensuing severity of flood damage suggests that a number of questions need to be addressed regarding the efficacy and flexibility of these procedures. Discussion of the pertinent questions follows the presentation of our conclusions and recommendations.

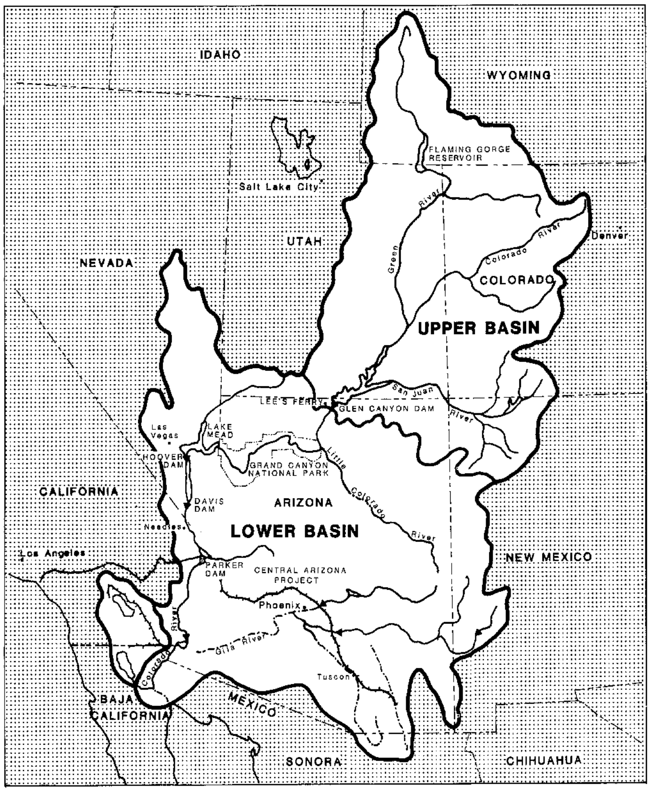


Fig 1 The Colorado River Basin

## Conclusions

1. The USBR conformed to the existing flood control regulations and established operating criteria, although the criteria didn't mandate the creation of sufficient flood storage reservation considering the high system storage conditions.

2. Because of the unusual weather in the April–June (1983) period and given the existing data collection network, forecasting procedures, and knowledge of watershed response, it was nearly impossible to anticipate the changing runoff conditions.

3. Advanced flood control releases in the fall and winter of 1982–83 would have provided for the evacuation of additional flood control storage. This additional flood control reservation could have attenuated peak flows and reduced the severity of beach erosion through Grand Canyon National Park.

4. Because of high system-wide reservoir storage, USBR realized as early as October 1982 that reservoir spills would occur if above-average runoff conditions were experienced in 1983.

## Recommendations

1. Reexamine the flood control regulations and reservoir operating criteria in light of the extremely high reservoir levels and changing projections of Colorado River Basin water demands.

2. Give more consideration to the biological and physical values of the Grand Canyon in formulating new flood control, power generation, and operating criteria for the reservoirs in the Colorado River system. Special attention should be directed to evaluating the effect of reservoir operations on sediment transport and beach erosion.

3. Study possible procedures which could increase co-ordination between reservoir operators and forecasting agencies to increase the speed and efficiency of system response to rapidly changing weather and runoff conditions.

4. Reevaluate the mathematical models used to develop snowmelt runoff forecasts by the National Weather Service's Colorado River Basin Forecast Center.

5. Expand the current network of telemetered data collection stations and extend the snow course measurement period when late season snowpack conditions warrant it.

## Pertinent Questions and Discussion

**Could the unusually high inflows to the Colorado River system reservoirs have been anticipated?**

The unusual weather events, along with the highly efficient nature of the snowmelt runoff, contributed to the generation of far more runoff than could have otherwise been anticipated using the existing data collection network and forecasting procedures.

Forecasts of inflow to the major reservoirs are provided to the USBR by the National Weather Service's Colorado River Forecast Center in Salt Lake City. Forecasts of cumulative April through July inflow to Lake Powell are made progressively throughout the normal period of snowpack accumulation and melt from January 1 to July 1. These forecasts are based on data collected monthly from snow courses, precipitation stations, and streamflow stations located throughout the Upper Basin States. Supplemental data is received from telemetered, or real time, measurement stations that are of more recent origin and are less reliable due to their short period of record. Following compilation of the data, National Weather Service hydrologists utilize mathematical models of watershed response and streamflow routing procedures to generate estimates of inflows to the major reservoirs [1)].

During 1983, the mountain snowpack continued to accumulate through April and May, reaching a maximum snow water equivalent in the middle of May. Significant snowmelt runoff did not begin until mid-May and was accompanied by heavy rains in portions of the Upper Basin.

Tab 1 USBR forecasts for first half year 1983

| Date of Forecast | April – July Runoff Forecast Million Cubic Meters, mio. $m^3$ (1 mio $m^3$ = 800 ac-ft.) | Percent of 15-Year Average 1963–77 |
|---|---|---|
| January 1 | 9,621 | 112 |
| February 1 | 8,758 | 102 |
| March 1 | 8,265 | 96 |
| April 1 | 9,745 | 114 |
| May 1 | 9,991 | 117 |
| June 1 | 11,220 | 131 |
| June 13 | 13,940 | 163 |
| June 20 | 16,650 | 194 |
| June 28 | 18,010 | 210 |

Source: Chief Engineer's Report to the Colorado River Board of California, July 5, 1983

Tab 1 summarizes the January 1 through June 28 forecasts received by the USBR.

January through March forecasts are necessarily tentative because they are made during the snowpack accumulation period. The April 1 forecast is considered a more reliable estimate since snowpack water equivalent normally reaches a maximum at about that time, with the subsequent inception of the melt season. A substantially reduced number of snow course measurements are typically available for use in developing the May 1 and later forecasts. Consequently, these late spring forecasts contain a higher degree of uncertainty and will vary in their predictive accuracy depending upon the actual efficiency of snowmelt runoff [2].

Considering the existing forecasting procedures, the USBR was provided with the best available inflow information as it became available. However, a number of shortcomings in these forecasting procedures can be identified:

- The limited real time data on precipitation and snow water equivalent
- The current telemetered station network has not been in service long enough to function as a reliable indicator
- The lack of an adequate number of snow course measurements in the late spring during years of late season snowpack accumulation
- Insufficient co-ordination between USBR, National Weather Service, and the Soil Conservation Service in the development and interpretation of forecasted reservoir inflows, including inter-basin routing of streamflow and projections of consumptive use in agriculture
- The current models of runoff efficiency lack both an adequate historical record and reliable estimates of streamflow depletions.

**Could the USBR have reduced the flood damage through reservoir regulation?**

Flood damage could not have been avoided by using the flood control regulations and operating criteria that were in place during the 1982–83 water year. By the time heavy runoff had been predicted, system storage was so high that damaging releases had to be made from both Glen Canyon and Hoover Dam. Insufficient flood control storage space was available to store the high inflows and attenuate the high releases. Although the USBR operated within the boundaries of current flood control regulations and operating criteria, the reservoirs could have been regulated to provide more flood control space. Given the ultimate timing and magnitude of the runoff, it is unlikely that flood damage could have been entirely avoided. Greater flood control storage reservation, however, could have delayed and, in the case of Glen Canyon, attenuated the damaging releases. A chronological summary of selected reservoir and system operations for October 1982 through June 1983 is shown in Tab 2. In October and November 1982, releases from Hoover were made only to meet downstream requirements despite record high system storage for the period.

During January, flood control regulations formulated by the Army Coprs of Engineers mandated flood control releases in anticipation of above-average (112 %) April–July runoff. Because February and March forecasts were near normal the USBR decided that no releases would be made from Hoover in excess of those required to satisfy downstream demands [3]. In response to the April 1 runoff forecast, the USBR extended its previous timetable for releases which were required to meet the system flood storage reservation requirement on January 1, 1984, from four months to nine months, commencing in April 1983.

Tab 2 Summary of Colorado Basin Reservoir Operations: October 1982 – July 1983

| End of Month | Active Storage[a] | Total System[b] Storage | System Flood[b,d] Control Reservation | Projected Most[f] Probable April-July Inflow to Lake Powell | System Storage over Month | Relases[a] |
|---|---|---|---|---|---|---|
| | (Million cubic meters) | | | | | |
| October 1982 | 28,450<br>28,460 | 66,950[c] | 7,438 | – | + 307 | 978.66[e]<br>484.27 |
| November 1982 | 28,190<br>29,130 | 67,260 | 7,475 | – | + 305 | 1,205.00<br>467.99 |
| December 1982 | 27,900<br>29,790 | 67,520 | 6,679 | 9,621 | + 265 | 1,207.30<br>572.10 |
| January 1983 | 27,640<br>29,510 | 66,720 | 7,420 | 9,128 | – 802 | 1,129.60<br>1,450.80 |
| February 1983 | 27,420<br>30,140 | 66,840 | 7,420 | 8,388 | + 121 | 1,064.90<br>499.86 |
| March 1983 | 27,880<br>30,390 | 67,570 | 6,686 | 9,745 | + 730 | 820.65<br>781.30 |
| April 1983 | 28,100<br>30,330 | 67,690 | 6,686 | 9,991 | + 116 | 1,175.60<br>1,306.30 |
| May 1983 | 29,870<br>30,530 | 70,320 | 4,490 | 11,220 | + 2,629 | 1,554.50<br>1,769.00 |
| June 1983 | 32,280<br>32,050 | 75,510 | 0 | 18,010 | + 5,197 | 4,007.30<br>2,326.80 |

* Source: Colorado River Water Reports – Colorado River Board of California
a Upper value is for Lake Powell, lower for Lake Mead
b Major system reservoirs only: figures are slightly less than actual
c Total available system storage equals approximately 8,141 mio. $m^3$ (6.6 million acre-ft). Source: Alden Briggs, USBR, Boulder City, Nev.
d January 1 minimum required flood control storage reservation is 6,599 mio. $m^3$
e Includes Pariah River inflow (24.7 $m^3$) at Lee Ferry
f Preliminary or final forecast depending on which was cited

On May 1, a continuing upward trend in the forecasts forced the USBR to further increase release volumes from both Lake Powell and the Lower Basin mainstream reservoirs with the average discharge reaching nearly 566 cubic meters per second ($m^3/s$) below Hoover and nearly 510 $m^3/s$ (1 cfs = .28317 $m^3/s$) below Parker Dam. At release levels above approximately 651 $m^3/s$, some impairment in the use of recreational facilities below Parker Dam is initiated. Nearly all of the major system reservoirs filled during June. Beyond 793 $m^3/s$ damage to permanent structures results[4)]. Thus, inflows were passed through the reservoirs, with Lake Powell spilling its peak discharge of 2,568 $m^3/s$ on June 29. Releases from Hoover Dam ranged from approximately 481 $m^3/s$ to 1,104 $m^3/s$ during the first three weeks in June. Then on June 25–26, heavy rainstorms over the Upper Colorado River Basin increased the final predicted April-July runoff to 210 % of the long-term average. Flood control releases from Hoover in excess of 1,133 $m^3/s$ began during early July and were expected to last through September[5)] (Fig 2).

**Why didn't the system possess enough flood control storage reservation to handle the heavy late spring and early summer runoff?**

The flood control storage space was inadequate because the reservoir storage levels were already at record high levels by June 1, 1983, before the majority of the snow runoff flowed into the reservoirs. Current flood control regulations only mandate that the USBR reserve a minimum of 6,599 million cubic meters (mio. $m^3$) of flood control storage space in the system reservoirs by January 1 of each year and 1,850 mio. $m^3$ of flood control storage space in Lake Mead on August 1 each year. Flood control releases are required only when runoff forecasts indicate that these storage goals might not be met by normally scheduled releases. Other than these mandated releases, the USBR can schedule releases as it desires as long as they are in accordance with long-range operating criteria and the priorities established by Congressional directive.

On January 1, the system-wide flood control reservation requirement of 6,599 mio. $m^3$ was met, albeit with

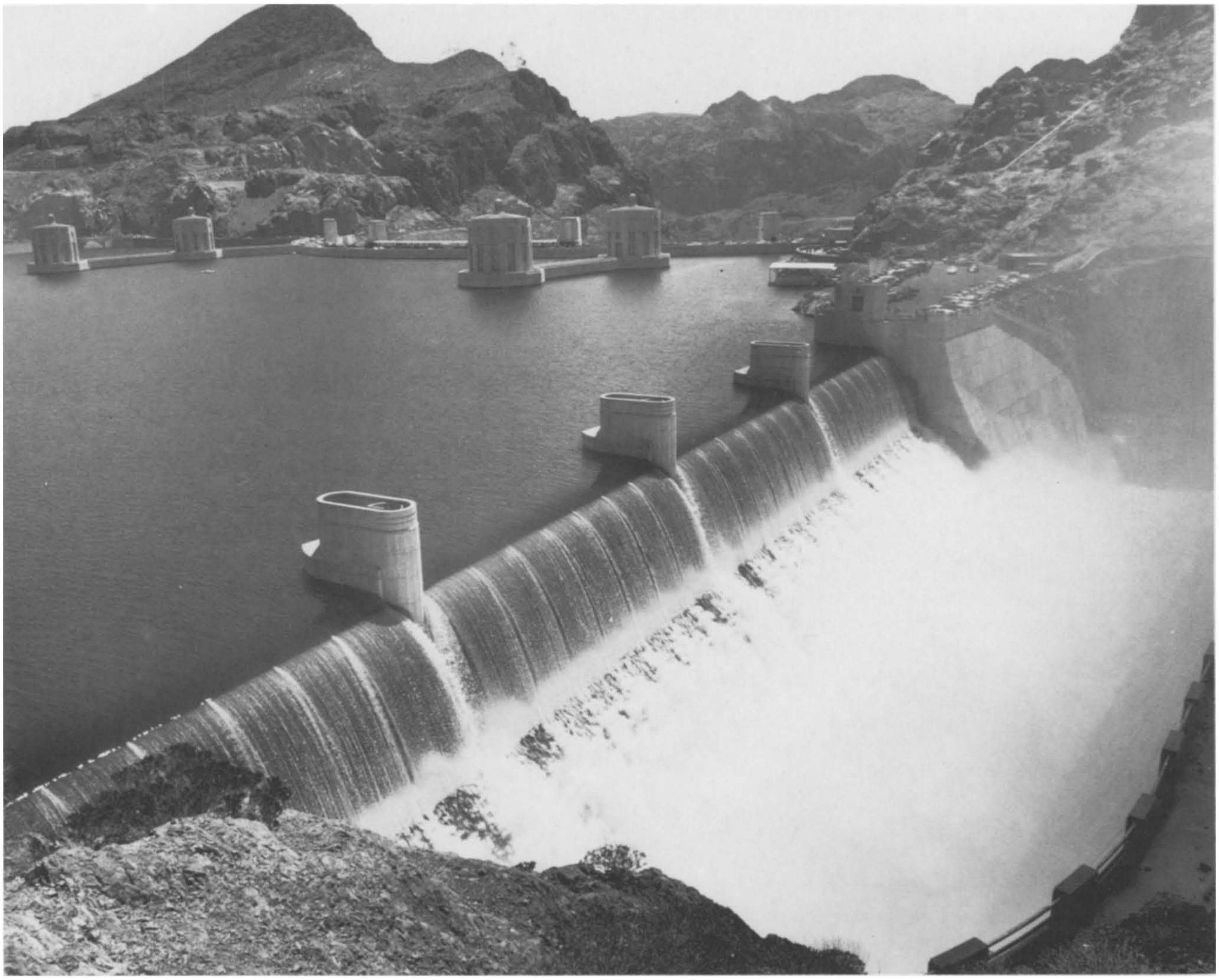

Fig 2 Nevada spillway at Hoover Dam discharging at its peak capacity of 395 $m^3/s$. – Since 1941, Hoover Dam's spillway has been dry. (Photo: J.E. Kingsley, US Bureau of Reclamation)

little margin of safety. In fact, January 1 cumulative system storage for the major reservoirs in the Colorado River Basin was the highest on record [6]. Until the filling of Lake Powell in 1980, system demand for additional flood storage space could be partially satisfied through staged increases in reservoir storage at Lake Powell. As early as October 1982, USBR operations staff were aware that even a normal runoff year in the Colorado River Basin could force January 1, 1984, flood storage reservation levels down to the absolute minimum requirement of 6,599 mio. $m^3$ [7]. Thus, above normal runoff during 1983 would in all likelihood necessitate controlled spills from system reservoirs, resulting in the bypassing of system power plants and potential downstream flooding [8]. To accommodate their concerns the USBR suggested to the Colorado Compact states (California, Arizona, Nevada, Utah, Colorado, New Mexico, Wyoming) that advanced flood control releases in the winter of 1983 would be advisable [9]. The USBR used this type of advanced or anticipatory release concept in 1980 to prevent the necessity of mandated flood control releases later in the year. Unfortunately, the Upper Basin states were hesitant to approve advanced flood control releases during the first three months of 1983 unless absolutely necessary. For some time, there has been general agreement among the states regarding the desirability of maintaining total system reservoir storage at as close to maximum levels as possible, to provide for efficient delivery of water to the Central Arizona Project when diversions begin

Tab 3 Comparison of 1982–83 Actual and Alternative Release Schedules for Glen Canyon and Hoover Dams

| | 1982–3 Actual Release Schedule[a] | | | | | | 1982–3 Alternative Release Schedule[d] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total (mio. $m^3$) | | Mean[b] ($m^3$/s) | | Peak Daily ($m^3$/s) | | Total (mio. $m^3$) | | Mean ($m^3$/s) | | Peak Daily ($m^3$/s) | |
| | Glen Canyon | Hoover | Glen Canyon | Hoover | Glen Canyon | Hoover | Glen Canyon | Hoover | Glen Canyon | Hoover | Glen Canyon | Hoover |
| Nov | 1,181 | 468 | 456 | 181 | 582 | N.A. | 1,688 | 1,688 | 651 | 651 | 651 | 651 |
| Dec | 1,176 | 572 | 439 | 214 | 593 | N.A. | 1,744 | 1,744 | | | | |
| Jan | 1,127 | 1,451 | 421 | 542 | 648 | 716 | 1,744 | 1,744 | | | | |
| Feb | 1,052 | 450 | 435 | 186 | 647 | 300 | 1,576 | 1,576 | | | | |
| Mar | 815 | 781 | 304 | 291 | 411 | 552 | 1,744 | 1,744 | | | | |
| Apr | 1,173 | 1,307 | 452 | 504 | 643 | 705 | 1,688 | 1,688 | | | | |
| May | 1,527 | 1,769 | 570 | 561 | 724 | 756 | 1,744 | 1,744 | | | | |
| Jun | 4,271 | 2,327 | 1,648 | 898 | 2,588 | 1,113 | 3.081 | 1,688 | 1,189[e] | 651 | 1,189 | 651 |
| Jul | 4,379 | 3,175 | 1,635* | 1,185* | 2,471 | 1,439 | 3,184 | 3,034 | 1,189 | 1,133 | 1,189 | 1,133 |
| Aug | 2,723[c] | 3,025 | 1,020*[c] | 1,129 | N.A. | 1,294 | 2,829 | 3,034 | 1,056[f] | 1,133 | 1,056 | 1,133 |

a Source: Colorado River Water Report, Colorado River Board of California, Dec. 1982 – July 1983; Chief Engineer's Monthly Report to the Colorado River Board of California, Nov. 1982 – Aug. 1983; and Bureau of Reclamation Reservoir Status Reports for Colorado River Storage Project and Lower Colorado Region, Nov. 1982 – Aug. 1983

b Figures represent powerplant releases except where indicated by asterisk (*) which includes additional spilled release bypassing powerplant

c Estimate assuming 20 days at 1,133 $m^3$/s + 11 days at 816 $m^3$/s (approx. powerplant maximum)

d Assuming tributary inflow remains equal to actual condition

e Calculated on basis of total number of days in June (14) and July (20) where powerplant bypass releases were required after satisfaction of the storage volume gained grom Nov.–May advanced releases, i.e. (651 $m^3$/s –– actual) over each month

f Estimated assuming 20 days at 1,189 $m^3$/s + 11 days at 816 $m^3$/s

N.A. = not available at time of writing

sometimes in 1985–6 [10]. Therefore, aside from mandated flood control releases in January, advanced releases were not made during February or March. This operational plan resulted in system storage increases in these months, as shown in Tab 2. Subsequent April 1 system storage was greater than than extant on January 1; i.e., the system flood storage reservation decreased further even prior to the onset of the snowmelt runoff season. As was previously discussed, the USBR did advance the timetable for scheduled flood control releases, beginning in April. However, in retrospect, the operating criteria that was followed failed to provide for an acceptable margin of safety regarding available flood storage reservation given the system storage levels which existed in the fall and winter of 1982 and 1983.

**Would it have been reasonable to have implemented an alternative release schedule in order to reduce the severity of flood damage?**

Although the USBR manages reservoir operations in accordance with established flood control regulations and operating criteria, these guidelines do give the USBR some flexibility in scheduling monthly flows.

An alternative release schedule based on the concept of advanced flood control releases could have been implemented concurrently at Glen Canyon and Hoover dams beginning in November of 1982. This schedule is outlined in Tab 3 and would have provided for approximately 3,947 and 1,480 mio. $m^3$ of additional flood storage reservation at Lake Powell and Lake Mead, respectively [11]. A continuous release of 651 $m^3$/s was assumed for the November through May period for both reservoirs based on the maximum non-damaging flow downstream of Hoover Dam [12]. Since an equivalent release was assumed for both reservoirs, additional discharge from Glen Canyon partially negated the increase in the flood storage reservation gained by increased releases from Lake Mead. The release rates for June through July were estimated on the basis of actual release volumes less the amount compensated for by the additional May 1 flood storage reservation. Continuous releases from Glen Canyon for the alternative schedule were computed to be approximately 1,133 $m^3$/s through August. For Hoover, the alternative schedule required continuous releases of 651 $m^3$/s in June and greater than or equal to 1,133 $m^3$/s thereafter. According to current USBR projections, September releases are scheduled to continue at an average rate of about 1,133 $m^3$/s. Thus, the additional flood storage reservation at Hoover Dam afforded by the alternative release schedule would have provided minimal reduction in the downstream flood flows which actually occurred. In summation, the alternative release schedule would have provided for a significant reduction in the magnitude of late spring and summer flows within the Grand Canyon. Under the same schedule, damaging releases from Hoover Dam would have been only slightly delayed, but not significantly attenuated.

A second scenario could have been enacted whereby advanced releases would have been made only from Hoover Dam. For a continuous release of 651 $m^3/s$ from November through May, a total increase in evacuated flood storage at Lake Mead of about 5,427 mio. $m^3$ could have been realized. Although an accounting of reservoir storage was not completed for this scenario, its effect would have been to further delay and possibly reduce the magnitude of damaging releases below Hoover Dam.

**What impact could reasonably achieved increases in flood storage space have had on flood damage within Grand Canyon and on the Lower Colorado River?**

The release figures for the alternative schedule appearing in Tab 3 indicate that advanced flood control releases during late 1982 and early 1983 could have affected the magnitude and/or duration of damaging flood flows downstream of Glen Canyon and Hoover Dams.

With construction of the major dams on the Colorado River, the prevailing flow regime was drastically altered. Prior to this spring's flood, an adjustment in the morpholoy of the River had resulted, although insufficient time had elapsed for the reach downstream of Glen Canyon Dam to achieve a new equilibrium. However, the ongoing process of scour and fill induced by the regulated release of sediment-free water from Lake Powell led to the establishment of beaches and their attendant biological communities within Grand Canyon National Park. In addition to this natural adaptation to the altered flow regime, human adaptation also began in earnest. Ill-advised settlement of the floodplain downstream of the false security so often perceived, although not always realized, by people seeking to take advantage of a "tamed" river.

If the alternative release schedule in Tab 3 had been followed, the damage to the ecology of the Grand Canyon could have been reduced. With scouring releases kept at approximately 1,133 $m^3/s$, less than half of that realized, the areal extent of beach erosion would have been decreased. Destruction of riparian vegetation could have been significantly diminished. Regardless of which schedule in Tab 3 were followed, it appears unlikely that the flood damage downstream of Hoover Dam could have been avoided. It is possible, however, that under the alternative schedule, the higher damaging releases could have been delayed by about one month. Some resulting benefit would thus have been accrued by allowing more time for preparation to minimize major flood damage.

## Epilogue

The severe flooding along the Colorado River during the spring and summer of 1983 sparked public debate on the issue of reservoir operational strategies and long-term management priorities. Congressional hearings were held in late summer and early fall to evaluate the Bureau's operational procedures during the preceeding year and to enable residents and representatives of the flooded Lower Basin communities to voice their concerns and frustations. Meanwhile, USBR staff grappled with pressing immediate concerns: repair of major structural damage to the spillway tunnels at Glen Canyon due to sustained high flows, and evacuation of sufficient flood storage space in the major mainstem reservoirs to accommodate inflows during the upcoming 1984 runoff season.

In November of 1983, USBR Commissioner Robert Broadbent recommended to the Basin-state representatives a target January 1, 1985 flood storage reservation of 9,250 mio. $m^3$, substantially above the currently mandated minimum of 6,600 mio. $m^3$. To facilitate reservoir drawdown and to ensure adequate flood storage space, the Commissioner also recommended that January–March 1984 releases from Lake Mead correspond to the conservative prediction of an upper-quartile runoff for that period. Negotiations between the USBR and representatives for the Compact states on water supply contingencies and Hoover Dam spillway maintenance eventually lead to a reduction in the January 1, 1985 target flood storage reservation to 8,140 mio. $m^3$. However, the Bureau's anticipatory flood control releases appeared prudent, as an unusually heavy early winter snow accumulation inflated the ensuing January 1, 1984 forecast of April–July inflow to Lake Powell to 16,000 mio. $m^3$, 175 % of the long-term average Aside from temporary declines during February and March, the April–July inflow forecasts continued to rise. As of August 1, the estimated final April–July inflow is about 18,700 mio. $m^3$, or approximately 208 % of the long-term average. This estimated volume exceeds the 17,900 mio. $m^3$ inflow computed for the 1983 runoff season. Moreover, the total virgin flow for 1983–84 is assured to surpass the recorded maximum virgin flow for two consecutive years, which occurred during 1920–21. It appears that, to date, the sustained high releases from Glen Canyon and Hoover Dams during the fall, winter and spring of 1983–84 and the installation of spillway flashboards at Glen Canyon (which increased reservoir storage by approximately 2,870 mio. $m^3$) attenuated the peak flows experienced during June and July of 1984. Releases from Glen Canyon and Hoover Dams in 1984 peaked during late June at 1,218 $m^3/s$ and 1076 $m^3/s$ respectively. As in 1983, 1984 releases from Hoover, which were maintained at or above 793 $m^3/s$, required the use of the designated lower Colorado River floodway.

From a long-term management perspective, the internal review process catylized by the historic flooding in 1983 should enhance the Bureau's ability to operate system reservoirs more efficiently and safely. Some projects that have been initiated or aided as a result of the flooding include:

1) Construction of air slots in the spillway tunnels at Glen Canyon Dam, which suffered extensive cavitation damage during 1983.

2) Similar maintenance on the spillways at Hoover Dam. Although no significant damage occurred to them during 1983, future sustained high flows could render them structurally disabled.

3) Initiation of a new long-term operational study for system reservoirs which will, for the first time, include both the use of synthetically generated streamflows in mathematical simulation and correction of existing, overly optimistic estimates of virgin flows on the Colorado.

4) Derivation and validation by the National Weather Service of a revised, higher runoff uncertainty factor, which is added to the mean runoff forecast to produce a maximum forecast.

5) A Colorado River sediment transport study focused on the River reach through Grand Canyon National Park. Enactment of an environmentally compatible reservoir operations policy will become a possibility with the completion of this study. However, given the multitude of competing interests, negotiations on the issue and likely to be complex and arduous.

6) An effort by the USBR to gain support and funding for an increase in staffing at its Colorado River Forecasting Center in Salt Lake City, Utah, and for installing a network of automated weather stations. This would improve streamflow forecasts by providing daily, rather than weekly or monthly, water supply forecasts and, therefore, more accurate forecasts through use of newly constructed predictive models.

7) Legal designation of a functional floodway extending downstream of Hoover Dam. A bill (HR5055) has been introduced this year in the US Congress which will most likely designate a 1,133 $m^3/s$ floodway through this effected reach. Passage of the bill would bring about a restriction in the federal disaster assistance available to occupants in the floodway.

## Footnotes

1) Dave Westnedge, Deputy Hydrologist in Charge, NWS, Colorado Basin River Forecast Center; and Tony Hefer, Hydrologist, Regional Office, NWS – phone conversations. The April–July inflow forecasts are based on "most probable" estimates which correspond to a statistical probability of occurrence of 95 %; i.e., there is a 5 % change that inflows will be greater than predicted. Three forecasts are normally provided to the USBR every month during the snowpack accumulation and melt season. A preliminary first of the month forecast based on evaluation of 10–15 % of the data is followed by a final first-of-the-month forecast based on evaluation of all the available data. Then a mid-month forecast representing a further adjustment of the final first of the month forecast is provided only to the USBR for the purpose of facilitating operational adjustments.
2) Snowmelt runoff efficiency will vary from year to year, depending upon a number of factors including plant evapotranspiration, soil moisture deficiency, snowpack evaporation, and unmeasured streamflow depletions.
3) The USBR did not receive its first reliable estimates of reduced mainstream water demands until early in April. Reduced consumptive use by agriculture and the Payment-in-Kind (PIK) program were largely responsible for this lowering of Basin water demand. The PIK program compensated farmers for land kept out of production. (cf. GeoJournal 8.2, 185–187 (1984))
4) Alden Briggs, Chief, Water Scheduling Branch, USBR, Boulder City, Nevada. Phone conversation. Damaging flows between Hoover and Parker dams begin at 1,133 $m^3/s$.
5) A substantial portion of the subsequent flood damage to communities downstream of Hoover Dam, especially below Parker Dam, could probably have been avoided had past construction in the established floodway been prohibited. Without the inhibitory effect of floodplain settlement on May and June releases from Lake Mead and the other Lower Basin reservoirs, flood storage evaluation could have been stepped up, and downstream flood flows in excess of 1,133 $m^3/s$ might have been unnecessary.
6) Source: Colorado River Water Reports, Colorado River Board of California, 1980–1983.
7) Ann Ball, USBR, Salt Lake City, phone conversation, September 1, 1983.
8) Ibid.
9) It appears that the advanced releases the USBR thought would be necessary in 1983 were not enough considering the increase in system storage experienced in 1982 when runoff was about normal.
10) Source: Chief Engineer's Monthly Report to the Colorado River Board of California, October 9, 1981, and December 3, 1982.
11) Approximate gains in the flood storage reservation in millions of cubic meters at Glen Canyon based on 651 $m^3/s$ continuous release; and gains (or losses) from Lake Mead based on (a) conjunctive release of 651 $m^3/s$ and (b) 651 $m^3/s$ release for Lake Mead with actual release rates from Glen Canyon:

| | | November | December | January | February |
|---|---|---|---|---|---|
| Glen Canyon | | 507.33 | 568.30 | 624.93 | 523.31 |
| Hoover, | a) | + 712.92 | + 603.88 | – 324.01 | + 602.23 |
| | b) | 1,220.20 | 1,172.20 | 293.52 | 1,125.50 |

| | | March | April | May | Total |
|---|---|---|---|---|---|
| Glen Canyon | | 929.78 | 515.62 | 218.05 | + 3,887.30 |
| Hoover, | a) | + 342.05 | –134.69 | + 24.65 | + 1,519.20 |
| | b) | 963.99 | 380.94 | 242.70 | + 5,399.10 |

June, July, and August of 1983 saw actual releases in excess of 651 $m^3/s$; therefore, flood storage gains were restricted to the above period.
12) This ceiling on non-damaging releases assumes that the inflow to Parker Dam is bypassed in total; i.e. no regulation of the inflow would occur. During the winter months, some regulation of inflow would usually occur.