ANL/EA/PP--83550

EFFECTS OF FLAMING GORGE DAM HYDROPOWER OPERATIONS ON DOWNSTREAM FLOW, STAGE, AND SEDIMENT TRANSPORT*

S.C.L. YIN, D. TOMASKO, H.E. CHO, G. WILLIAMS
Argonne National Laboratory, Argonne, Illinois 60439, USA

J. McCOY and C. PALMER
Western Area Power Administration, Salt Lake City, Utah 84147, USA

*Work supported by the U.S. Department of Energy, Western Area Power Administration, under contract W-31-109-Eng-38.

DISCLAIMER

ABSTRACT

Hydropower operations at Flaming Gorge Dam, located on the Green River in Utah, can produce rapid downstream changes in flow and stage. These changes can in turn affect sediment transport and ecologic resources below the dam. To evaluate these effects, four hydropower operational scenarios with varying degrees of hydropower-release fluctuations were examined. This study demonstrates that the combined use of river-flow routing, water-surface profile, and sediment-transport models can provide useful information for evaluating the potential impacts of hydropower operations on ecological and other resources downstream of the dam. Study results show that flow fluctuations may or may not persist for a long distance, depending on the initial magnitude of fluctuation and the duration of hydropower peaking. Stage fluctuations depend not only on flow fluctuations but also on river channel characteristics, such as channel width and longitudinal slope.

KEY WORDS:

Flaming Gorge Dam

Flow Routing

Green River

Hydrology

Hydropower

Sediment Transport

INTRODUCTION

The Western Area Power Administration (Western) markets electricity produced at hydroelectric projects operated by the U.S. Bureau of Reclamation (Reclamation) on the Upper Colorado River, including Flaming Gorge Dam on the Green River in Utah (Figure 1). This paper presents the development of release patterns and resulting downstream flows, stages, and sediment transport for four hydropower operational scenarios proposed for the dam. The results of this study are useful for assessing potential impacts of the hydropower operational scenarios on riparian vegetation, trout, and native fishes of the Green River (LaGory and Van Lonkhuyzen, 1994; Hlohowskyj and Hayse, 1994).

Flaming Gorge Dam, completed in 1963, is part of the Colorado River Storage Project and is used for hydropower production. The study area extends from Flaming Gorge Dam to a streamflow gaging station near Jensen, Utah, about 150 km downstream of the dam (Figure 1). This reach was chosen to be consistent with the biological opinion of the U.S. Fish and Wildlife Service (1992) on the operations of Flaming Gorge Dam, which specifies allowable flow fluctuations below the dam and target flows at the Jensen gage. A biological opinion is a document that states the opinion of the U.S. Fish and Wildlife Service as to whether or not a U.S. government action is likely to jeopardize the continued existence of listed species under the Endangered Species Act or result in adverse impacts on critical habitat.

RESERVOIR RELEASE PATTERNS

Four hydropower operational scenarios for Flaming Gorge Dam were considered in this study: (1) year-round high fluctuating flows, (2) seasonally adjusted high fluctuating flows, (3) seasonally adjusted moderate fluctuating flows, and (4) seasonally adjusted steady flows. The year-round high fluctuating flow scenario assumes that the monthly total reservoir releases would be the same as historical releases. The maximum and minimum daily releases, including power and nonpower, would be limited only by the water available for release, the minimum release requirement, and the power plant capacity. The maximum power release of 133 m^3/s is limited by the capacity of the turbines, whereas a minimum release of 22.6 m^3/s is set by an agreement with the state of Utah to maintain a high-quality cold-water fishery. Flows greater than 133 m^3/s, which can be released through dam outlets and the spillway, are referred to as spills and produce no electric power.

The remaining three scenarios assume seasonally adjusted flows that would comply with the biological opinion and would include high flows in the spring and limited hourly fluctuations, especially in summer and autumn releases, to protect downstream populations of endangered fish. For the seasonally adjusted steady flow scenario, reservoir releases would be constant throughout the day in each season, with a season defined by the biological opinion as a period of variable length, ranging from several weeks to one month.

Table I presents allowable daily release fluctuations for summer and autumn. Each daily release pattern is expressed in terms of a base and a peak release rate, with one hour on-peak. The minimum allowable base release and maximum allowable peak release for each season (month or partial month) were determined with the Streamflow Synthesis and Reservoir Regulation (SSARR) computer model (discussed later) being used by Reclamation for the Green River below Flaming Gorge Dam. Selection of the target flows shown in Table I was based on the biological opinion constraints.

In addition to constraints on fluctuations for summer and autumn releases, the biological opinion also requires altering the historical seasonal pattern of release to provide high flows in

Table I. Allowable release fluctuations for Flaming Gorge Reservoir

Year/Month	Average Yampa River Flow[a] (m^3/s)	Target Flow at Jensen[b] (m^3/s)	Daily Reservoir Release[c] (m^3/s)			Daily Flow at Jensen Gage[d]			
			Average	Base Flow	Peak Flow	Minimum (m^3/s)	Percent Below Target	Maximum (m^3/s)	Percent Above Target
1987 (Moderate)									
Jul 10-31	12.0	42.5	30.0	25.2	82.1	37.4	12.0	47.6	12.0
Aug	9.20	42.5	32.8	28.0	84.9	37.4	12.0	47.8	12.5
Sep	6.85	42.5	35.1	30.3	87.8	37.4	12.0	47.8	12.5
1989 (Dry)									
Jun 20-30	38.2	31.1	22.6	22.6	22.6	-[e]	-	-[e]	-
Jul	8.86	31.1	26.0	22.6	64.6	31.4	0.0	38.8	24.8
Aug	4.39	31.1	30.3	26.9	68.0	31.4	0.0	38.8	24.8
Sep	2.86	31.1	31.7	28.3	69.4	31.4	0.0	38.8	24.8
1983 (Wet)									
Jul 20-31	98.0	51.0	22.6	22.6	22.6	-[e]	-	-[e]	-
Aug	39.6	51.0	22.6	22.6	22.6	-[e]	-	-[e]	-
Sep 1-15	15.7	51.0	28.3	22.6	92.0	38.5	24.5	51.0	0.0
Sep 16-30	9.43	68.0	48.7	41.6	125	51.0	25.0	68.0	0.0

[a] As recorded at the Deerlodge Park gage.

[b] Based on the biological opinion (U.S. Fish and Wildlife Service, 1992).

[c] Base and peak flows were determined such that the maximum and minimum flows at the Jensen gage would comply closely with the constraint of 25% fluctuations around the target flows at the gage. The reservoir also has a minimum release requirement of 22.6 m^3/s.

[d] Flows computed with the SSARR model.

[e] Flows at the Jensen gage were not computed for cases where the reservoir releases would be constant at 22.6 m^3/s.

the spring and low flows in the summer and autumn. When ice cover is present on the Green River below the dam (assumed to be February and March), no hourly fluctuations would be allowed. More details regarding the criteria used to derive the release rates are presented in Yin et al. (1994). Reservoir release patterns were developed for three representative hydrologic years that were selected on the basis of streamflow records: moderate (1987), dry (1989), and wet (1983). Each release pattern has a minimum release for a certain duration starting at midnight, ramp up to a maximum release in one hour, hold at the maximum for an on-peak duration of variable length, and then ramp down in one hour to the minimum release. The on-peak period is assumed to center around 4:00 p.m. Table II summarizes the release patterns in a moderate hydrologic year for an average day in each season.

RIVER FLOWS AND STAGES BELOW THE DAM

Flows in the Green River and the corresponding river stages resulting from reservoir releases under the four operational scenarios were estimated for five locations below Flaming Gorge Dam for the moderate hydrologic year. The SSARR model for the Green River was used to calculate hourly downstream flows, and a water-surface profile model for estimating river stages was developed with the HEC-2 computer program (U.S. Army Corps of Engineers, 1982).

River flow

The SSARR model for the Green River was used to estimate river flows between Flaming Gorge Dam and the Jensen gage for different operational scenarios. The model uses the flow-routing portion of the SSARR computer program to route river flow hydrographs through river channels

Table II. Daily reservoir release patterns for a moderate hydrologic year, 1987

	Year-Round High Fluctuation				Seasonally Adjusted High Fluctuation			Seasonally Adjusted Moderate Fluctuation			Seasonally Adjusted Steady Flow (m^3/s)
Period	Minimum Release (m^3/s)	Maximum Release (m^3/s)	On-Peak Duration (hours)	Average Release (m^3/s)	Minimum Release (m^3/s)	Maximum Release (m^3/s)	On-Peak Duration (hours)	Minimum Release (m^3/s)	Maximum Release (m^3/s)	On-Peak Duration (hours)	
Oct	22.6	133	10	73.3	22.6	22.6	0	22.6	22.6	0	22.6
Nov	22.6	133	17	105	22.6	133	9	62.9	118	1	67.4
Dec	22.6	133	17	105	22.6	133	9	62.9	118	1	67.4
Jan	22.6	133	12	91.7	22.6	133	9	62.9	118	1	67.4
Feb	22.6	133	14	91.7	67.4	67.4	24	67.4	67.4	24	67.4
Mar	22.6	133	2	36.5	67.4	67.4	24	67.4	67.4	24	67.4
Apr	22.6	133	2	36.5	22.6	133	10	69.1	124	1	73.6
May	22.6	133	4	45.6	22.6	133	15	77.6	133	7	96.0
Jun 1-21	22.6	133	2	36.5	133	133	24	133	133	24	133
Jun 22-30	22.6	133	2	36.5	22.6	133	17	78.4	133	11	106
Jul 1-9	22.6	133	4	45.6	22.6	133	6	52.7	108	1	57.2
Jul 10-31	22.6	133	4	45.6	25.2	82.1	1	27.6	56.1	1	30.0
Aug	22.6	133	3	41.1	28.0	84.9	1	30.6	58.9	1	32.8
Sep	22.6	133	5	50.4	30.3	87.8	1	32.8	61.2	1	35.1

(U.S. Army Corps of Engineers, 1987). The user specifies the number and routing characteristics of each segment. Routing through each segment is based on the law of continuity as expressed in the storage equation, which relates the change in storage to the average inflow to and average outflow from the segment. The outflow from each segment becomes the inflow to the next segment.

The study reach for the Green River between Flaming Gorge Dam and the Jensen gage was divided into five modeling reaches, with boundaries at Gates of Lodore, Hells Half Mile, Jones Hole, Rainbow Park, and the Jensen gage (Figure 1). The SSARR model was verified during this study by comparing the model-predicted flow with the recorded flow at the Jensen gage for the periods from April 1 to June 21, 1987, and from May 1 to June 30, 1992. The Yampa River is the only major tributary of the Green River between the dam and Jensen; its flow is accounted for in the model by assuming that its flow is equal to that recorded at the Deerlodge Park gage. The time interval used in the Green River SSARR model is one hour. Figure 2 shows the computed and recorded hourly flows at the Jensen gage. The correlation coefficients of the computed and recorded flows for the two verification periods are 0.96 and 0.98, respectively. Both the flow comparisons in Figure 2 and the correlation coefficients indicate that the model is relatively reliable. In particular, the model appears to predict reasonably well the general patterns of flow fluctuation at the Jensen gage.

The verified SSARR model for the Green River and the reservoir release patterns were used to calculate hourly flows at the selected downstream locations for the moderate hydrologic year for the four hydropower operational scenarios. The daily maximum and minimum flows at these locations are discussed below for the year-round and seasonally adjusted high fluctuating flow scenarios.

Under the year-round high fluctuating flow scenario, the maximum daily reservoir release fluctuation would be 110 m^3/s year-round (Figure 3). The fluctuations at Gates of Lodore would be reduced to about 30 to 82% of the fluctuation at the dam. The difference in the magnitude of reduction is mainly influenced by the on-peak duration of the reservoir release. A relatively short on-peak period, such as the two-hour duration in March, or a relatively long one, such as the 17-hour duration in November and December (Table II), tends to rapidly reduce the flow fluctuation. A medium on-peak duration, such as the 10-hour duration in October, tends to maintain a high fluctuation for a longer distance down the river. At downstream locations, further reductions in fluctuation would be minor. At the Jensen gage, the fluctuations would still be 27 to 77%. The flow patterns at the Jensen gage appear to be dissimilar to those at Gates of Lodore because of inflow from the Yampa River.

Under the seasonally adjusted high fluctuating flow scenario (Figure 4), the daily release fluctuations would range from 56.9 to 110 m^3/s, except that no fluctuation would be allowed in February and March (the assumed ice cover period), October would have a steady release of 22.6 m^3/s (the required minimum release), and June 1 through 21 would have a steady release of up to 133 m^3/s (as required by the biological opinion). The fluctuations at Gates of Lodore would be reduced to about 19 to 80% of the fluctuation at the dam. Similar to the year-round high fluctuating flow scenario, further downstream reductions in fluctuations would be minor. At the Jensen gage, the fluctuations would still be 17 to 78% of those at the dam.

River stage

Stages of the Green River were estimated for the maximum and minimum river flows resulting from reservoir releases under the four hydropower operational scenarios for the same locations for which the flows were calculated. The river stage at a particular location depends mainly on the river flow and channel geometry in the area. The stages were estimated with a water-surface profile model for the Green River using the HEC-2 computer program (U.S. Army Corps of Engineers, 1982). More detailed discussion of the water-surface model for the Green River is presented in Yin et al. (1994).

Maximum and minimum stages resulting from reservoir releases under the four operational scenarios were estimated from the river flows described earlier and the stage-flow relationships calculated with the water-surface profile model. Daily maximum and minimum stages above that for a flow of 22.6 m^3/s at Flaming Gorge Dam, Gates of Lodore, and Jensen gage are shown for the moderate hydrologic year (1987) in Figure 5 for the year-round high fluctuating flow scenario. Under this scenario, the daily stage fluctuations at the dam resulting from hydropower operations would be about 1.5 m year-round at Flaming Gorge Dam, about 0.73 to 1.5 m at Gates of Lodore, and reduced to about 0.18 to 0.61 m at the Jensen gage. Under the seasonally adjusted high fluctuating flow scenario, the daily stage fluctuations would be about 0 to 1.5 m at the dam, about 0 to 1.5 m at Gates of Lodore, and about 0 to 0.67 m at the Jensen gage. Under the seasonally adjusted moderate fluctuating flow scenario, the daily stage fluctuations would be about 0 to 0.67 m at the dam, about 0 to 0.64 m at Gates of Lodore, and about 0 to 0.27 m at the Jensen gage. Under the seasonally adjusted steady flow scenario, no daily stage fluctuations would result from hydropower operations (Yin et al., 1994).

SEDIMENT TRANSPORT

Sediment transport calculations were performed for the Green River to evaluate the impacts of the hydropower operational scenarios and historical flow regimes. Field and literature studies indicate that the part of the study area most susceptible to erosional impacts is Browns Park (Figure 1). Andrews (1986) presents approximately 20 years of recorded suspended sediment records for gages located on the Green and Yampa Rivers. These records indicate that the Green River picks up significant sediment load below the dam, before the Jensen gage.

Browns Park is the most sensitive area for erosional impacts within the study reach. The riverbed above this point is armored (fine riverbed and bank sediment have been removed by high-velocity water, leaving only sediment that is too heavy or coarse to be moved) and there is little sediment load from tributaries. The Green River is sediment starved when it reaches the alluvial banks and bed of Browns Park, causing increased rates of erosion (Williams and Wolman, 1984). Beginning at Browns Park, the river erodes large quantities of sand and silt from the alluvial banks and bed. Further downstream in Lodore Canyon, additional erosion occurs; however, because of the influx of sediment from Browns Park, the rate of erosion is lower. In addition, the channel is geologically confined by steep, hard rock walls. At the confluence of the Yampa River, an additional large quantity of sand is delivered to the system, further reducing downstream erosion. By the time the river reaches Jensen, Utah, a near-equilibrium condition has been established, with no net erosion or aggradation taking place (Andrews, 1986; Elliott et al., 1984).

Methodology

Sediment load for this study was calculated with the Engelund-Hansen method (Engelund and Hansen 1972). This model was selected because it requires a minimum amount of site-specific information, and it has been previously used to model the Green River with satisfactory results (Andrews, 1986).

A computer program was developed to compute the bed material load for the four hydropower operational scenarios. Input to the program consisted of hourly flow data for the scenarios and site-specific parameters. The program computed the sediment load transported during each one-hour time step. Stage-discharge relationships needed for the model were developed from the water-surface profile model, and channel characteristics were taken from U.S. Geological Survey quadrangle maps of the Browns Park area (U.S. Geological Survey, 1985). Further discussion of the Green River sediment model is presented in Williams et al. (1994).

Results of the sediment load calculations

Historical sediment loads were calculated with the Engelund-Hansen method for hydrologic years 1987 (moderate), 1989 (dry), and 1983 (wet). For the dry year, 100% of the load is transported by flows of less than 113 m^3/s. For the wet year, about 50% of the sediment load is transported by flows in excess of 227 m^3/s. Sediment loads for Browns Park were calculated to be about 0.94, 0.12, and 3.13 million tonnes for 1987, 1989, and 1983, respectively (Williams et al. 1994). The computed sediment load for the moderate hydrologic year (1987) is within 20% of the mean annual sediment loads estimated by Andrews (1986).

The sediment load for the alluvial reach of the Green River in the Browns Park area is shown in Table III for the moderate, dry, and wet years for the four hydropower operational scenarios. These sediment loads indicate that for a moderate year, impacts between the various operational scenarios are similar and lie within the expected accuracy of the transport model. Although the sediment loads for a dry year would all be greater than that for historical releases, the small associated volumes would preclude any significant impacts. In a wet year, the three seasonally adjusted operational scenarios would transport less sediment than historical releases. Year-round

TABLE III. Sediment discharges in the Browns Park area

Hydrologic Year	Operational Scenario	Annual Sediment Discharge (10^6 tonnes)	Percent Change from Historical
Moderate (1987)	Year-round high fluctuation	1.04	11
	Seasonally adjusted high fluctuation	1.00	6
	Seasonally adjusted moderate fluctuation	0.90	-4
	Seasonally adjusted steady flow	0.89	-5
Dry (1989)	Year-round high fluctuation	0.15	25
	Seasonally adjusted high fluctuation	0.26	120
	Seasonally adjusted moderate fluctuation	0.25	110
	Seasonally adjusted steady flow	0.24	100
Wet (1983)	Year-round high fluctuation	3.24	4
	Seasonally adjusted high fluctuation	2.36	-25
	Seasonally adjusted moderate fluctuation	2.34	-25
	Seasonally adjusted steady flow	2.34	-25

high fluctuations would transport sediment loads similar to historical releases. Because over a long time span, sediment transport occurs mostly in wet years, the seasonally adjusted operational scenarios might have less erosional impact than the year-round high fluctuating flow scenario.

CONCLUSIONS

This study has shown that the flow-routing model developed by Reclamation is a useful tool for predicting flow fluctuations in the Green River below Flaming Gorge Dam. This study also demonstrates that the combined use of river-flow routing, water-surface profile, and sediment-transport models can provide useful information for evaluating the potential impacts of hydropower operations on ecological and other natural resources downstream. Study results show that flow fluctuations may or may not persist for a long distance, depending on the initial magnitudes of fluctuation and durations of hydropower peaking. Stage fluctuations depend not only on flow fluctuations but also on river channel characteristics, such as channel width and longitudinal slope. The sediment transport modeling results indicate that the seasonally adjusted operational scenarios might have less erosional impact than the year-round high fluctuating flow scenario.

REFERENCES

Andrews, E.E. 1986. 'Downstream Effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah', *Geological Society of America Bulletin,* **97**, 1012-1023.

Elliott, J. G., Kircher, J. E., and Von Guerard, P. 1984. 'Sediment Transport in the Lower Yampa River, Northwest Colorado', *Water Resources Investigation Report 84-4141*, U.S. Geological Survey, Lakewood, Calif.

Engelund, F. and Hansen, E. 1972. *A Monograph of Sediment Transport in Alluvial Streams,* 3rd ed. rev., Teknisk Forlag, Copenhagen, Denmark.

Hlohowskyj, I. and Hayse, J. W. 1994. 'Effects of Flaming Gorge Hydropower Operations on the Fishes of the Green River, Utah and Colorado', *Argonne National Laboratory Report ANL/EAD/TM-11*, Argonne, Ill.

LaGory, K. E. and Van Lonkhuyzen, R. 1994. 'Effects of Flaming Gorge Dam Hydropower Operations on Riparian Vegetation of the Green River, Utah and Colorado', *Argonne National Laboratory Report ANL/EAD/TM-10,* Argonne, Ill.

U.S. Army Corps of Engineers. 1982. *HEC-2 Water Surface Profiles Users Manual*, Hydrologic Engineering Center, Davis, Calif.

U.S. Army Corps of Engineers. 1987. *User Manual: SSARR Model, Streamflow Synthesis and Reservoir Regulation*, North Pacific Division, Portland, Ore.

U.S. Fish and Wildlife Service. 1992. *Final Biological Opinion on the Operation of Flaming Gorge Dam*, Denver, Colo.

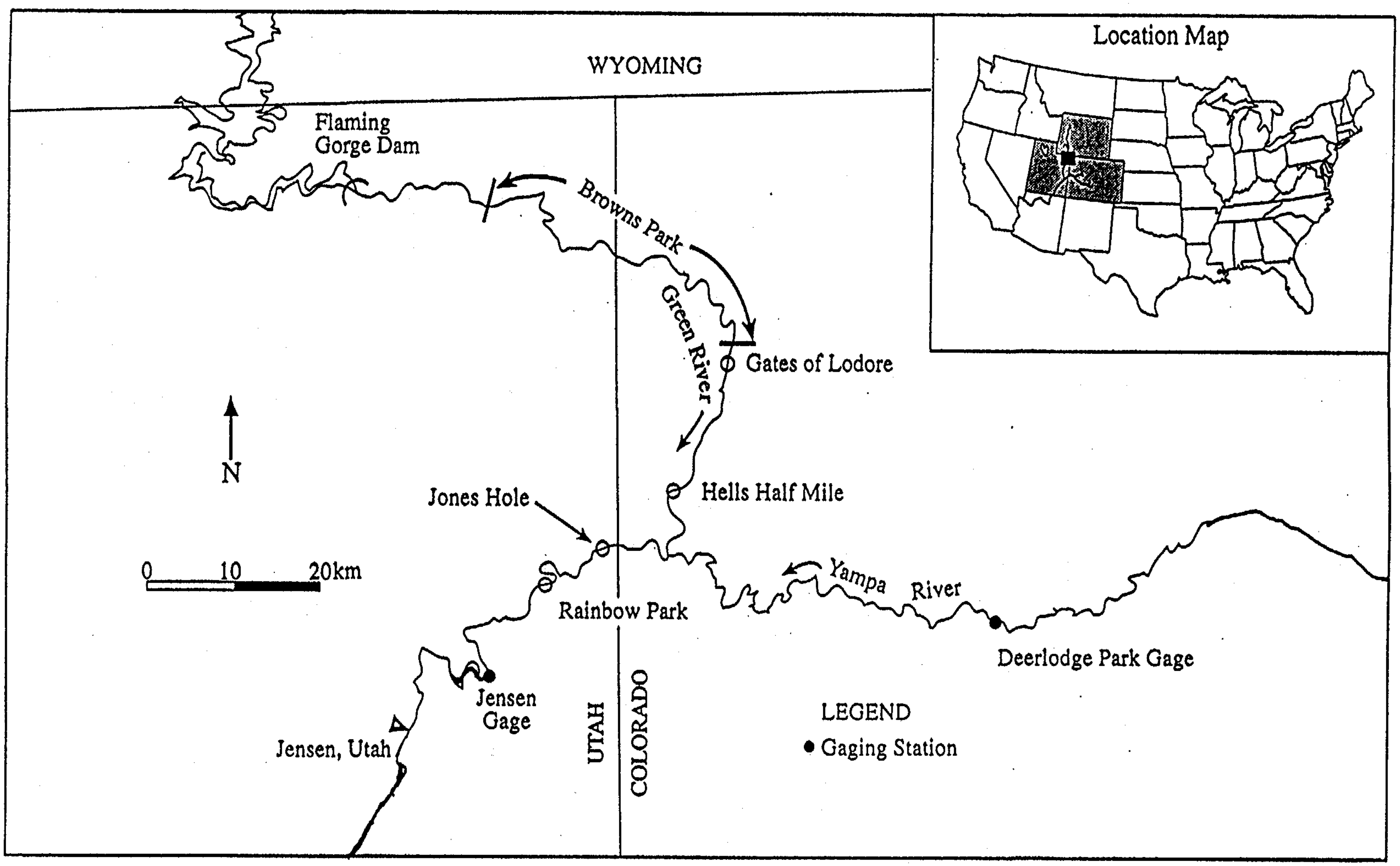
U.S. Geological Survey. 1985. *1:2,000,000 Hydrologic Unit Map of the Conterminous United States, Rev 1.1*, Reston, Va. (Accessed Dec. 20, 1991).

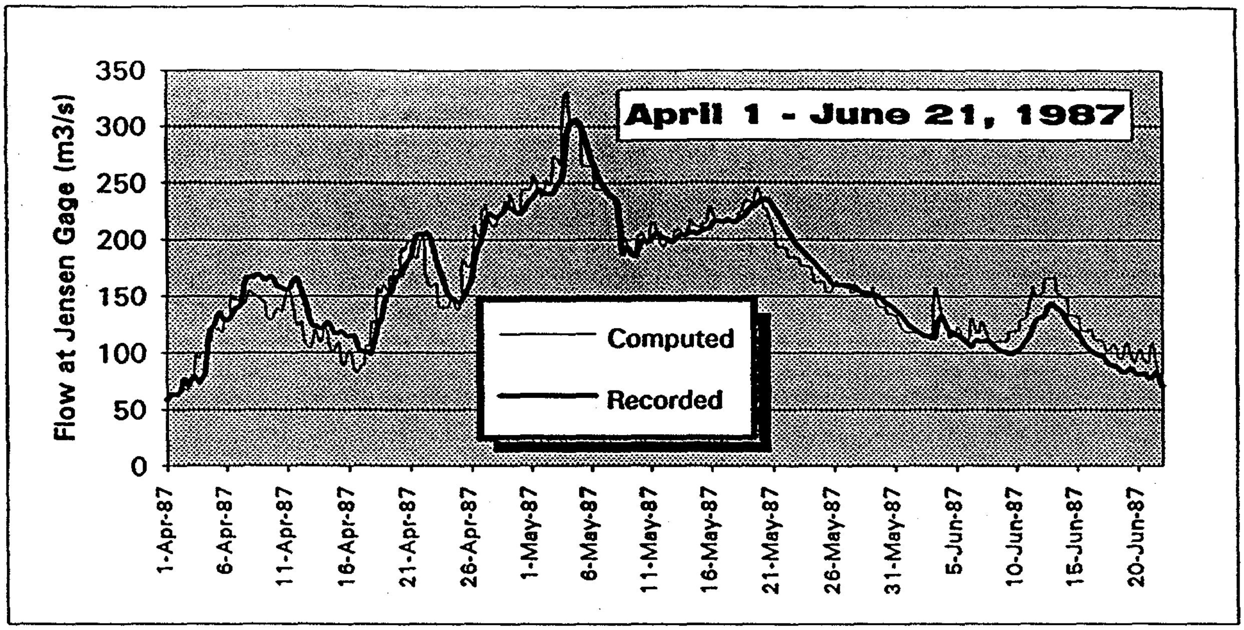
Williams, G. P. and Wolman, M. G. 1984. 'Downstream Effects of Dams on Alluvial Rivers', *U.S. Geological Survey, Professional Paper 1286*, Washington, D.C.

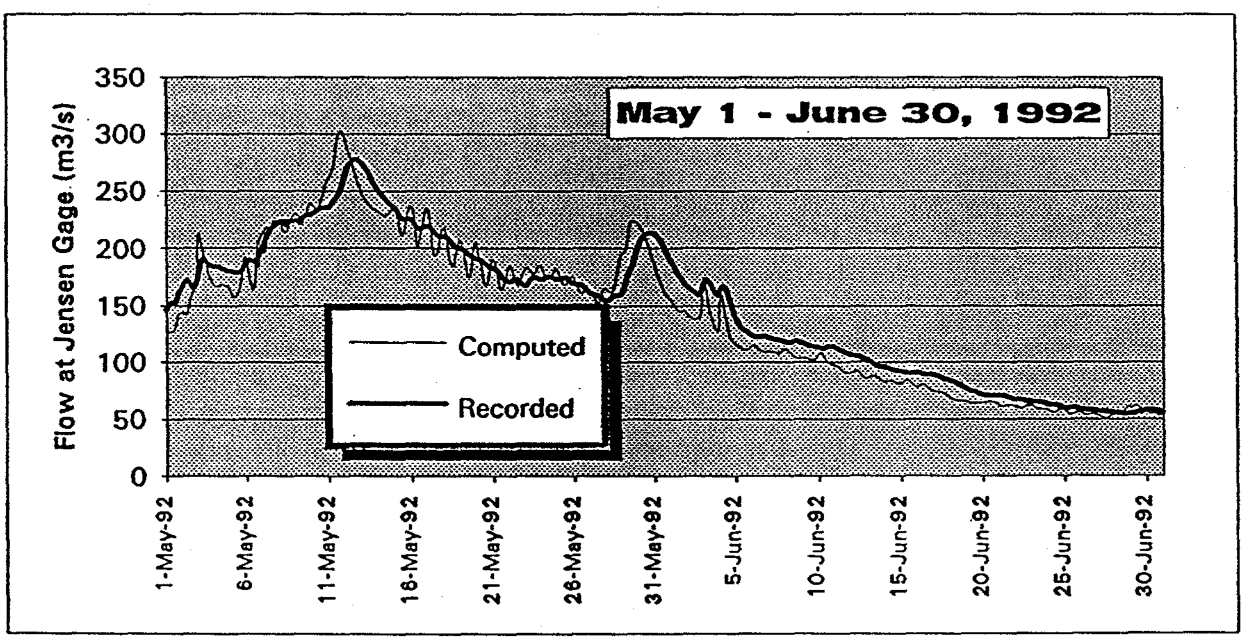
Williams, G. P., Tomasko, D., Cho, H. E., and Yin, S. C. L. 1994. 'Effects of Flaming Gorge Dam Hydropower Operations on Sediment Transport in the Browns Park Reach of the Green River, Utah and Colorado', *Argonne National Laboratory Report ANL/EAD/TM-6*, Argonne, Ill.

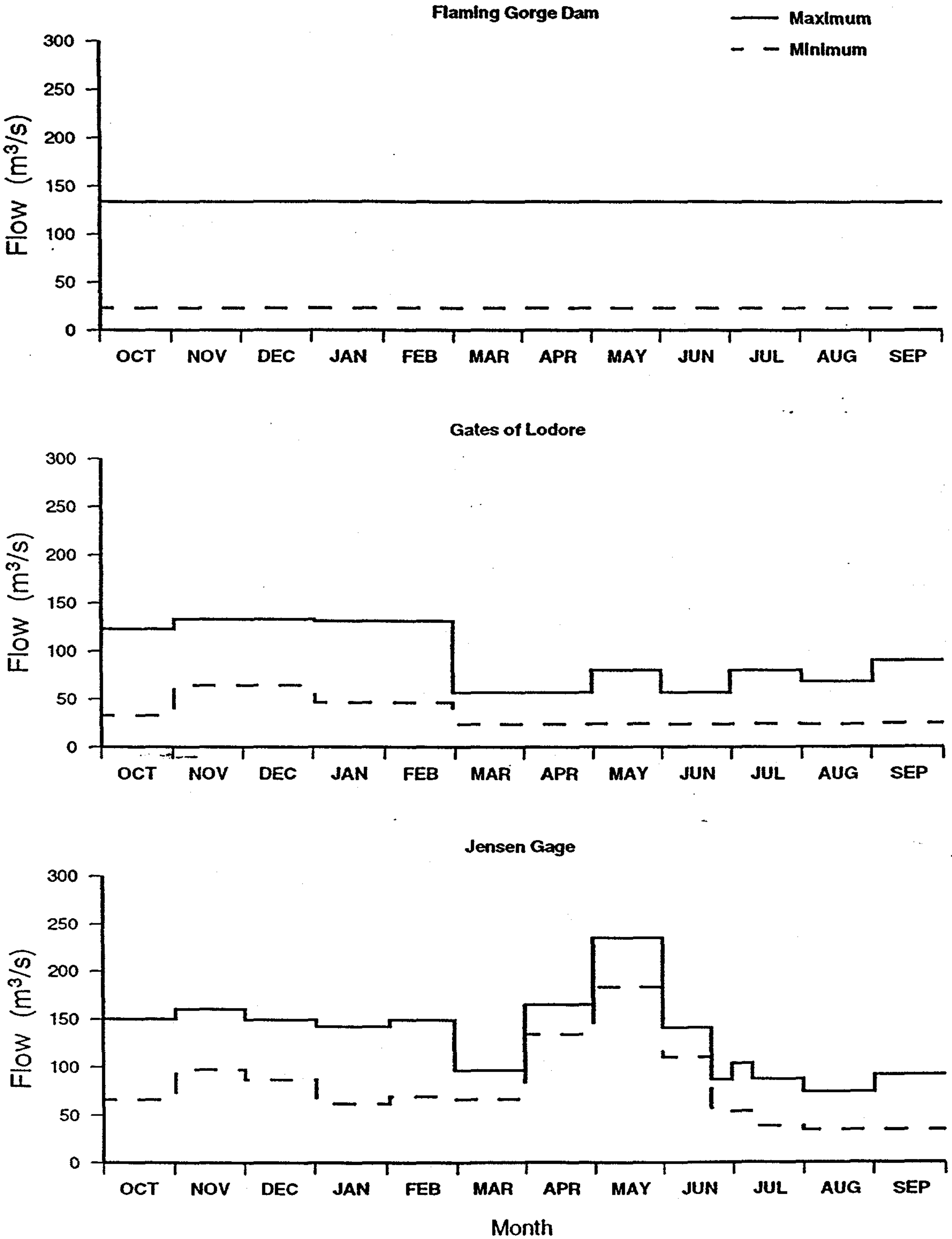
Yin, S. C. L., McCoy, J. J., Palmer, S. C., and Cho, H. E. 1994. 'Effects of Flaming Gorge Dam Hydropower Operations on Flow and Stage in the Green River, Utah and Colorado', *Argonne National Laboratory Report ANL/EAD/TM-4*, Argonne Ill.

FIGURES

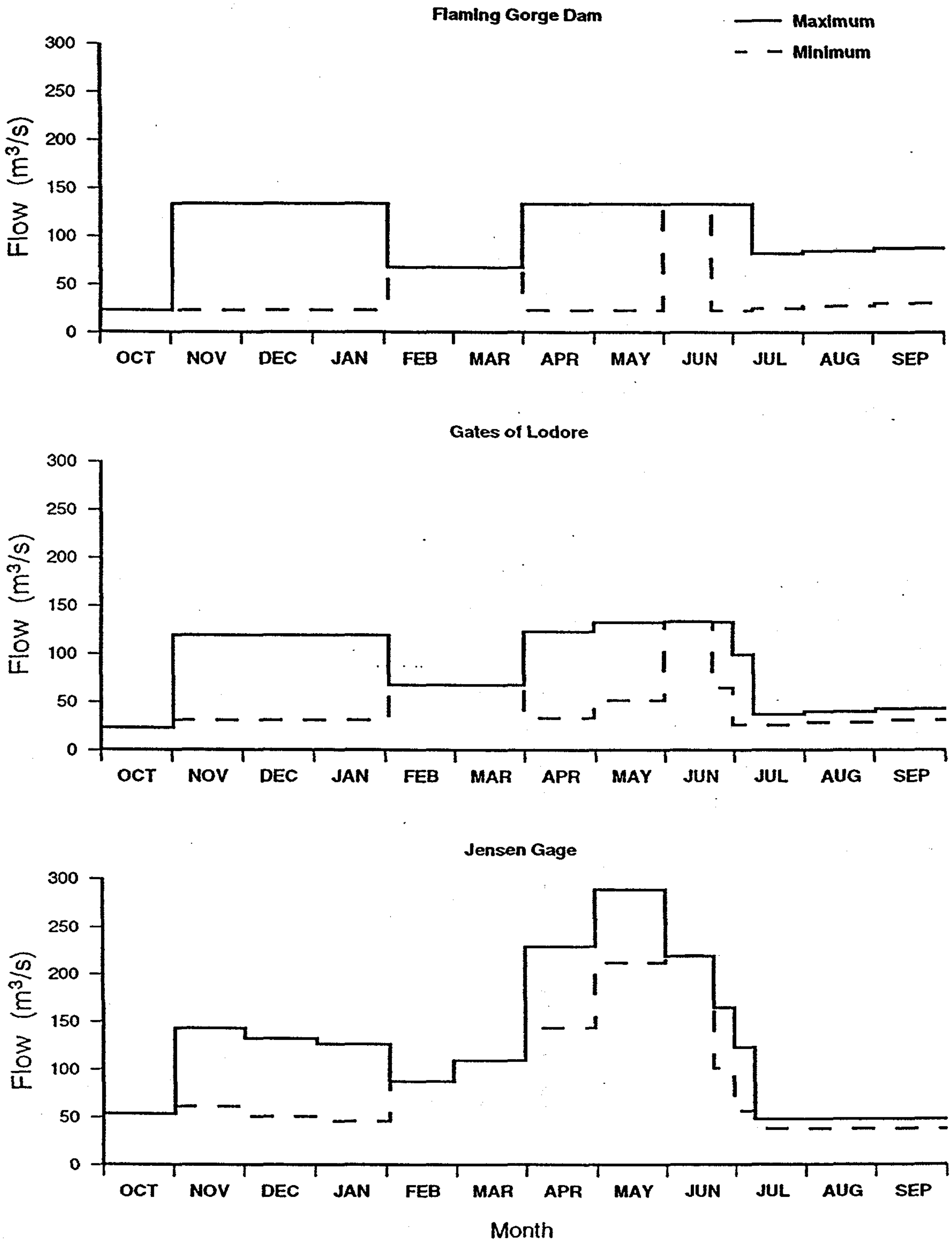

Location Map
WYOMING
Flaming
Gorge Dam
Browns Park
Green River
Gates of Lodore
Hells Half Mile
Jones Hole
Rainbow Park
Yampa River
Deerlodge Park Gage
Jensen
Gage
Jensen, Utah
UTAH
COLORADO
N
0
10
20km
LEGEND
● Gaging Station


April 1 - June 21, 1987
Flow at Jensen Gage (m3/s)
350
300
250
200
150
100
50
0
Computed
Recorded
1-Apr-87
6-Apr-87
11-Apr-87
16-Apr-87
21-Apr-87
26-Apr-87
1-May-87
6-May-87
11-May-87
16-May-87
21-May-87
26-May-87
31-May-87
5-Jun-87
10-Jun-87
15-Jun-87
20-Jun-87

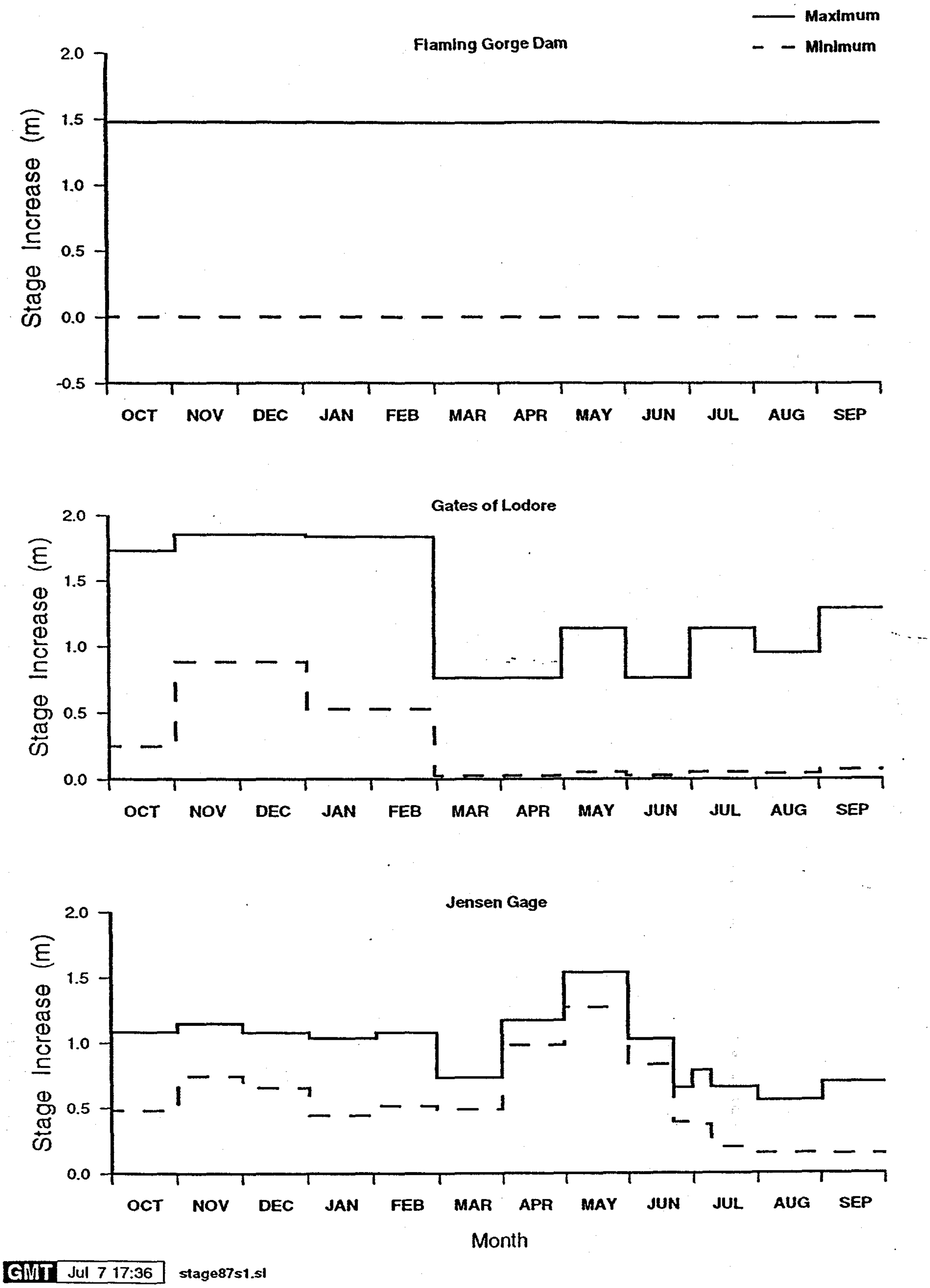

May 1 - June 30, 1992
Flow at Jensen Gage (m3/s)
350
300
250
200
150
100
50
0
Computed
Recorded
1-May-92
6-May-92
11-May-92
16-May-92
21-May-92
26-May-92
31-May-92
5-Jun-92
10-Jun-92
15-Jun-92
20-Jun-92
25-Jun-92
30-Jun-92



GMT Jul 8 14:05 fg87s1.sl



GMT Jul 8 14:08 fg87s2.sl


Maximum
Minimum
Flaming Gorge Dam
Gates of Lodore
Jensen Gage
Stage Increase (m)
2.0
1.5
1.0
0.5
0.0
-0.5
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
Month
GMT
Jul 7 17:36
stage87s1.sl