Calculated Hydrographs for Unsteady Research Flows at Selected Sites Along the Colorado River Downstream from Glen Canyon Dam, Arizona, 1990 and 1991

By Eleanor R. Griffin and Stephen Mark Wiele

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CONVERSION FACTORS

Multiply	By	To obtain
meter (m)	3.281	foot
square meter (m^2)	10.76	square foot
kilometer (km)	0.6214	mile
cubic meter per second (m^3/s)	35.31	cubic foot per second

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Abstract

A one-dimensional model of unsteady discharge waves was applied to research flows that were released from Glen Canyon Dam in support of the Glen Canyon Environmental Studies. These research flows extended over periods of 11 days during which the discharge followed specific, regular patterns repeated on a daily cycle that were similar to the daily releases for power generation. The model was used to produce discharge hydrographs at 38 selected sites in Marble and Grand Canyons for each of nine unsteady flows released from the dam in 1990 and 1991. In each case, the discharge computed from stage measurements and the associated stage-discharge relation at the streamflow-gaging station just below the dam (09379910 Colorado River below Glen Canyon Dam) was routed to Diamond Creek, which is 386 kilometers downstream. Steady and unsteady tributary inflows downstream from the dam were included in the model calculations.

Steady inflow to the river from tributaries downstream from the dam was determined for each case by comparing the steady base flow preceding and following the unsteady flow measured at six streamflow-gaging stations between Glen Canyon Dam and Diamond Creek. During three flow periods, significant unsteady inflow was received from the Paria River, or the Little Colorado River, or both. The amount and timing of unsteady inflow was determined using the discharge computed from records of streamflow-gaging stations on the tributaries. Unsteady flow then was added to the flow calculated by the model at the appropriate location.

Hydrographs were calculated using the model at 5 streamflow-gaging stations downstream from the dam and at 33 beach study sites. Accuracy of model results was evaluated by comparing the results to discharge hydrographs computed from the records of the five streamflow-gaging stations between Lees Ferry and Lake Mead. Results show that model predictions of wave speed and shape agree well with data from the five streamflow-gaging stations.

INTRODUCTION

In 1990 and 1991, twelve research flows were released from Glen Canyon Dam in support of the Glen Canyon Environmental Studies (GCES; table 1). Nine of these flows were unsteady flows, which fluctuated between a specified minimum and maximum discharge on a daily cycle (fig. 1). The other flows were steady. Several of the research flows varied between the same maximum and minimum discharges but differed in the rates of increasing and decreasing discharge (ramping rates).

The purpose of the research flows was to enable scientists and engineers to study the effects of various controlled flow conditions on the

Table 1. Dates and characteristics of the daily releases from Glen Canyon Dam for the unsteady research flows

[Discharge was computed from the record of the streamflow-gaging station, 09379910 Colorado River below Glen Canyon Dam. Up-ramp rate is the maximum rate of increase in dam releases on the rising limb of the daily hydrograph, and down-ramp rate is the maximum rate of decrease of dam releases on the falling limb]

Research flow	Periods of releases		Maximum discharge, in cubic meters per second	Minimum discharge, in cubic meters per second	Up-ramp rate, in cubic meters per second per hour	Down-ramp rate, in cubic meters per second per hour
	From	To				
A	10–01–90	10–11–90	368	71	76.2	–65.6
B	01–28–91	02–07–91	425	142	58.4	–46.3
C	12–31–90	01–10–91	566	226	73.1	–87.3
D	05–06–91	05–16–91	756	71	94.0	–149.2
E	09–17–90	09–27–90	756	71	154.9	–126.4
F1	07–16–90	07–26–90	792	226	90.9	–88.7
G1	07–02–90	07–12–90	792	226	156.1	–88.4
F2	07–15–91	07–26–91	792	226	91.7	–91.1
G2	07–01–91	07–11–91	792	226	149.8	–91.1

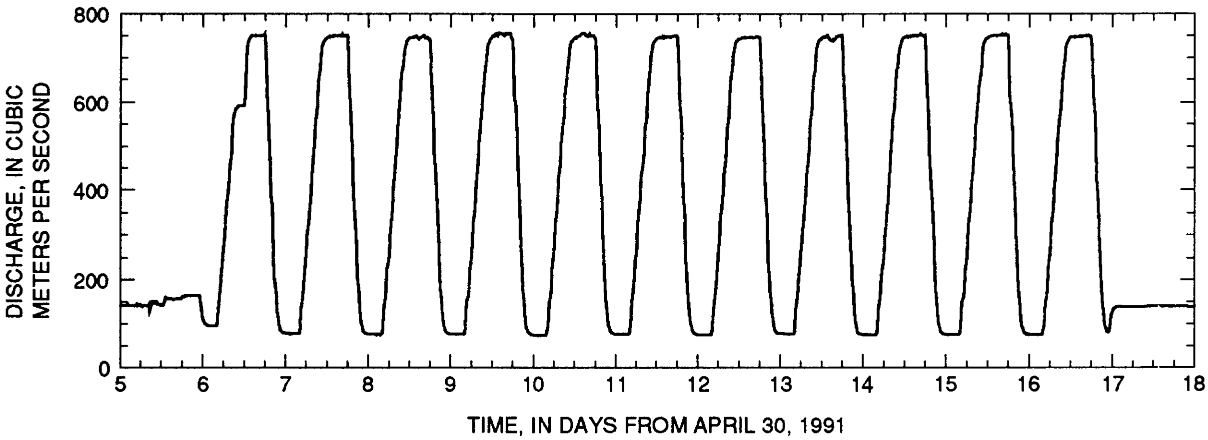

Figure 1. Discharge for an unsteady flow release from Glen Canyon Dam. Hydrograph was computed from the record for the streamflow-gaging station, Colorado River below Glen Canyon Dam (09379910), during research flow D, May 6, 1991, to May 16, 1991.

downstream environment. These studies were concerned with changes in the riparian habitat affecting vegetation, fish and wildlife, and changes to beach volumes resulting from erosion and deposition of sand. Flow information of interest in these investigations includes peak and trough discharges, rates of discharge increase and decrease, and time-of-arrival of the waves at downstream locations. The study was conducted by the U.S. Geological Survey (USGS) in cooperation with the Bureau of Reclamation.

The purpose of this report is to present hydrographs calculated using a one-dimensional unsteady-flow model for each of nine fluctuating GCES research flows released from Glen Canyon Dam in 1990 and 1991. The unsteady-flow model was used to calculate hydrographs at 5 streamflow-gaging stations on the Colorado River downstream from the dam (fig. 2) and at 33 beach study sites (table 2) during the 9 unsteady research flows. The model-calculated hydrographs were compared with the hydrographs computed from the gaging-station records. In addition, an analysis of the model results compared to data from the streamflow-gaging stations is provided as a measure of model accuracy.

DESCRIPTION OF THE FLOW MODEL

The one-dimensional unsteady-flow model used in this study was developed using data that included measured channel cross sections, reach-averaged velocities measured by dye tracing, measurements of stage and the associated stage-discharge relations at gaging stations, channel slope, and streamflow-gaging station information recorded during research flow B (January 28, 1991, to February 7, 1991). The model is based on large-scale, reach-averaged channel properties including a single characteristic channel cross section and an average slope (0.0015) for the entire 386-kilometer reach from Glen Canyon Dam to Diamond Creek. The development of the flow model is discussed in detail by Wiele and Smith (1995).

Because the model was tailored for the Colorado River through Marble and Grand Canyons, only discharge hydrographs (discharge as a function of time) are required as input. Except

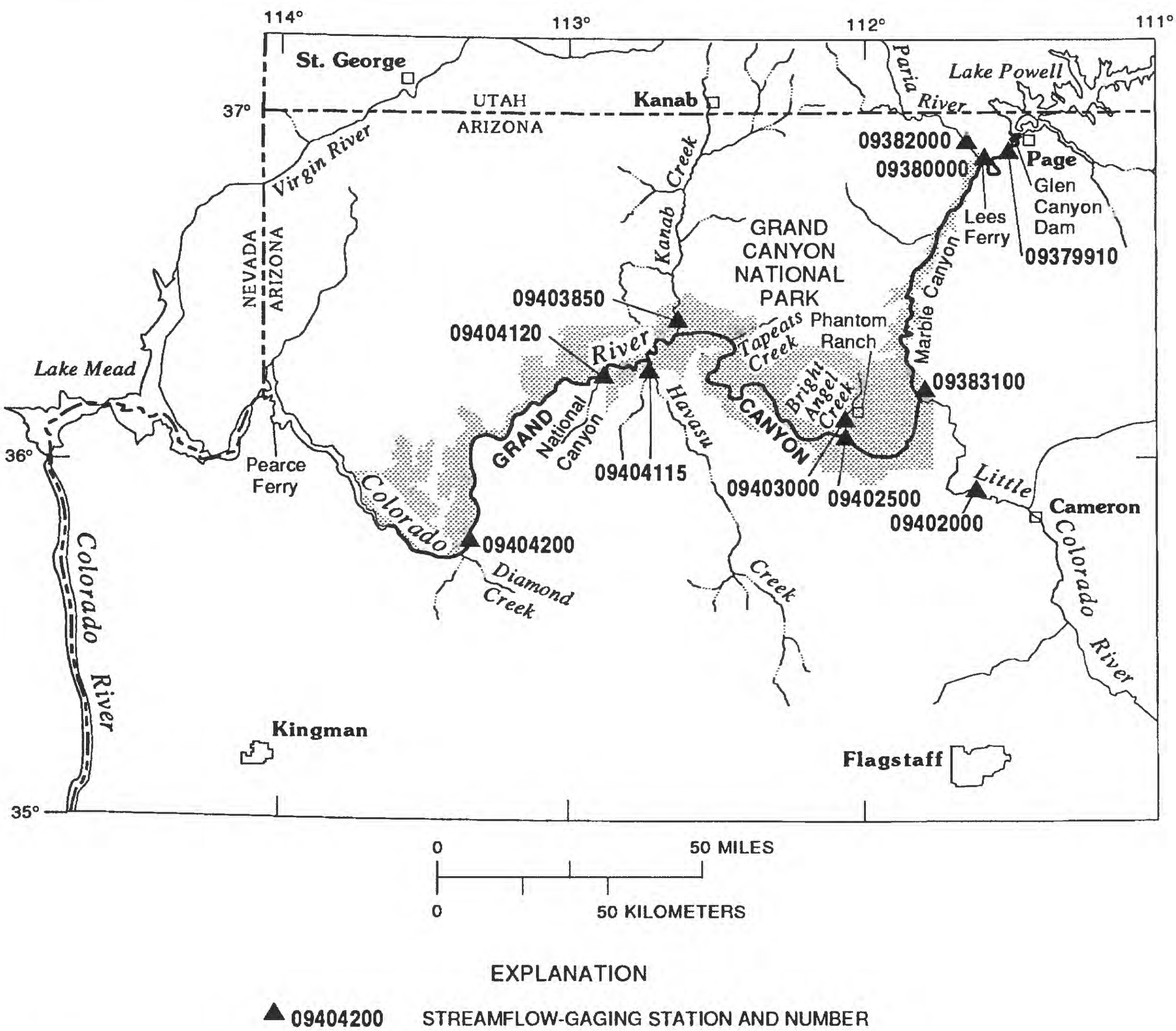

Figure 2. Locations of streamflow-gaging stations, Colorado River through Marble and Grand Canyons (modified from Graf, 1995).

Table 2. Selected locations for calculated hydrographs (beach study sites) and distance from Lees Ferry, Arizona

[Negative numbers indicate distance upstream from Lees Ferry; positive numbers indicate distance downstream from Lees Ferry. Locations from Kaplinski and others, 1995]

Study site name	River mile	Distance, in kilometers	Study site name	River mile	Distance, in kilometers
Hidden Sloughs	–6.5	–10	Upper Granite	93.0	149.6
3 mile	2.6	4.2	104 mile	103.9	167.2
Hot Na Na	16.4	26.4	119 mile	119.0	191.5
22 mile	21.8	35.1	122 mile	122.2	196.6
Fence Fault	30.0	48.3	Upper Forster	122.7	197.4
South Canyon	31.6	50.8	Middle Ponchos	136.7	220.0
33 mile	33.0	53.1	139 mile	139.0	223.7
Anasazi Bridge	43.0	69.2	145 mile	145.0	233.3
Eminence Break	45.0	72.4	172 mile	172.2	277.1
Lower Saddle	47.0	75.6	183 mile	182.8	294.1
Dino	50.0	80.5	194 mile	194.1	312.3
52 mile	51.5	82.9	202 mile	202.0	325.0
Crash Canyon	62.0	99.8	Pumpkin Springs	212.9	342.6
Tanner	68.0	109.4	Middle Gorilla	219.9	353.8
Grapevine	81.0	130.3	220 mile	220.0	354.0
Cremation	87.5	140.8	225 mile	225.0	362.0
91 mile	91.1	146.6			

during times of major flooding in the tributaries, flow is dominated by dam releases. Discharge hydrographs at the streamflow-gaging station at Colorado River below Glen Canyon Dam (09379910; RK 24, RM 15; fig. 1)[1], which were computed from stage measurements and the associated stage-discharge relation, are used as the upstream discharge-boundary condition. The streamflow hydrographs at this location typically are based on records with a 30-minute sampling interval. During research flows D, F2, and G2 (table 1), however, data were recorded at this gaging station in 15-minute time intervals. Discharges are interpolated to satisfy the model requirement of a 4-minute interval.

Tributary and ground-water contributions to the main-stem discharge also must be included in model calculations. Procedures for evaluating the magnitude and locations of tributary and ground-water contributions are described below. Contributions from these sources were added to the flow calculation of the model at the appropriate river mile.

Additional inflow from tributaries was determined primarily from the records of streamflow-gaging stations on the major tributaries to the Colorado River downstream from Glen Canyon Dam. Data were available from the following USGS streamflow-gaging stations: (A) 09382000, Paria River at Lees Ferry, Arizona; (B) 09402000, Little Colorado River near Cameron, Arizona; (C) 09403000, Bright Angel Creek near Grand Canyon, Arizona; (D) 09403850, Kanab Creek above the mouth, near Supai, Arizona; and

[1]The primary units in this paper are metric. Because location on the river commonly is given in river miles (RM) above (–) or below (+) Lees Ferry, locations and distances are given in river kilometers (RK) and river miles in this paper. The use of cubic feet per second for discharge is common and is clearly associated with stage at specific points along the river; therefore, discharges are given in cubic meters per second and cubic feet per second within the text.

(E) 09404115, Havasu Creek above the mouth, near Supai, Arizona (table 3 and fig. 2).

Some discrepancies involving the discharge computed from the stage record from the gaging station, 09379910 Colorado River below Glen Canyon Dam, that is used as model input affected the calculated hydrographs. During research flows A, E, F1, G1, F2, and G2, the discharge computed for the steady flow preceding the fluctuating flow using the stage record from the streamflow-gaging station, 09380000 Colorado River at Lees Ferry, and the associated stage-discharge relation was lower than the discharge computed for the steady flow using the record from the gaging station just below the dam. The greatest apparent decreases in steady discharge between the dam and Lees Ferry were recorded during research flows A and E. During flows A and E, the steady discharge computed from the stage recorded at the gaging station below the dam was 150 m^3/s (5,300 ft^3/s), and discharge computed from the stage recorded at the gaging station at Lees Ferry was 140 m^3/s (4,950 ft^3/s), which is a difference of 10 m^3/s (350 ft^3/s). For the remaining research flows, the deficit at Lees Ferry was 7 m^3/s (250 ft^3/s) or less. An apparent decrease in the steady discharge was recorded only at Lees Ferry.

Another irregularity in the data from the gaging station below the dam is in the record for research flow G1. The record shows that the peak discharge of the fourth wave released from the dam had a duration about twice that of the other waves during flow G1. This extended duration is not reflected in data from other streamflow-gaging station records, and therefore, was assumed to be an error in the record from the gaging station below the dam. The error does not extend beyond the trough following the fourth wave. Because the model was run using the discharge computed from the record of the gaging station below the dam as the upstream-boundary condition, the error in the fourth wave is present in all the calculated hydrographs for flow G1. Attempts were not made to correct this error because it was confined to only one of eleven daily waves, and the correction of streamflow records in the USGS data base was considered outside the scope of this study.

Steady Inflow from Tributaries

Steady inflow to the river from tributaries and ground-water sources downstream from the dam can be identified from the steady flows that preceded and followed fluctuating flows and from the magnitudes of the peaks and troughs of the unsteady flows. If inflow is steady, the peaks and troughs will have the same magnitude through the research-flow period, and the steady main-stem flow that follows the fluctuating flow will have the

Table 3. Gaged tributaries of the Colorado River between Glen Canyon Dam and Diamond Creek

Streamflow-gaging station number	Tributary name and gaging-station location	Distance downstream from Lees Ferry		Streamflow-gaging station number	Tributary name and gaging-station location	Distance downstream from Lees Ferry	
		River miles	Kilometers			River miles	Kilometers
09382000	Paria River at Lees Ferry, Arizona	1	2	09403850	Kanab Creek above mouth, near Supai, Arizona	144	232
09402000	Little Colorado River near Cameron, Arizona (45 miles above mouth)	61	98	09404115	Havasu Creek above mouth, near Supai, Arizona	157	253
09403000	Bright Angel Creek near Grand Canyon, Arizona	88	142				

same magnitude as the steady flow that precedes the fluctuating flow. The magnitude of the steady inflow was determined by taking the difference between the steady flow recorded at the streamflow-gaging station, 09379910 Colorado River below Glen Canyon Dam, and discharges recorded at five streamflow-gaging stations farther downstream from the dam and upstream from Lake Mead (fig. 2): (A) 09380000, Colorado River at Lees Ferry (RK 0); (B) 09383100, Colorado River above the Little Colorado River near Desert View (RK 98, RM 61); (C) 09402500, Colorado River near Grand Canyon (RK 142, RM 88); (D) 09404120, Colorado River above National Canyon near Supai (RK 267, RM 166); and (E) 09404200, Colorado River above Diamond Creek near Peach Springs (RK 362, RM 225).

Records from the gaging stations on the tributaries (table 3) were first examined to identify the sources of additional inflows. Steady inflow determined from data recorded at these gaging stations was added to the model calculation at the location of the mouth of the tributary, in kilometers, downstream from Lees Ferry. In some cases, the inflow determined from the record at these gaging stations did not account for the total increase in steady flow. For those cases, the remaining difference between the discharge at the gaging stations along the Colorado River during the steady flow was determined, then added to the model at locations of likely sources (for example, Tapeats Creek at RK 216 (RM 134) on the Colorado River; table 4).

Unsteady Inflow from Tributaries

Data from Streamflow-Gaging Stations

Records of the streamflow-gaging stations along the Colorado River show clear evidence of unsteady inflow during research flows C, E, and F1. The presence of unsteady inflow is indicated by varying peak and trough discharges during the research flow. Unsteady inflow data were obtained from streamflow-gaging stations on the Paria and Little Colorado Rivers, which appear to be the only sources of significant unsteady inflow during these periods. Records of the other tributary gaging stations (table 3) also were checked for unsteady inflow. The available records, however, indicated these tributaries were not significant sources of unsteady inflow during any of the research flows. The unsteady discharge from the Paria and Little Colorado Rivers was added to the model calculation for flows C, E, and F1.

During research flow C, the inflow from the Little Colorado River was greater than 55 m^3/s (1,900 ft^3/s) for slightly more than 1 day and peaked at 76 m^3/s (2,700 ft^3/s; fig. 3). Inflow from the Little Colorado River during the remainder of flow C generally was less than 20 m^3/s (710 ft^3/s). Because of the duration and magnitude of this inflow, the hydrographs for the Colorado River computed from the records of the gaging stations near Grand Canyon and above National Canyon (fig. 4*B* and *C*) show a significant increase in the peak and trough discharges of the research flow with the inflow from the Little Colorado River. The hydrograph computed from the record of the gaging station at Lees Ferry shows no evidence of unsteady inflow during this period. The timing of the increase in peak and trough discharges reflected in the records from the gaging stations was useful in determining the time of arrival of the inflow from the Little Colorado River into the Colorado River. The hydrographs computed from the records of the gaging station near Grand Canyon were useful particularly for inferring the timing of the unsteady inflow into the main stem. The method used to estimate the timing of the inflow added to the model calculation is discussed later in this report. Significant inflow from the Paria River or other gaged tributaries did not occur during research flow C.

The unsteady inflow from the Paria River during research flow E consisted of a single peak of short duration (less than half a day) with a maximum discharge of about 20 m^3/s (710 ft^3/s). The unsteady inflow from the Little Colorado River during research flow E was a series of peaks occurring over a 6-day period; one peak was greater than 80 m^3/s (2,800 ft^3/s; fig. 5). The flow of greatest magnitude on the Little Colorado River was about 120 m^3/s (4,200 ft^3/s). The time of arrival of the highest peak at the Colorado River during research flow E coincided with the arrival of a wave released from the dam. The actual arrival of the unsteady inflow from the Little Colorado

Table 4. Amount and location of steady inflows used for model hydrograph calculations

[Dashes indicate no data]

Research flow	Glen Canyon Dam to Lees Ferry (RK -24–0)	Lees Ferry to Little Colorado River (RK 0–98)		Little Colorado River to near Grand Canyon (RK 98–142)		Near Grand Canyon to above National Canyon (RK 142–268)		Above National Canyon to Diamond Creek (RK 268–362)	
		Inflow, in cubic meters per second	Location, in river kilometers	Inflow, in cubic meters per second	Location, in river kilometers	Inflow, in cubic meters per second	Location, in river kilometers	Inflow, in cubic meters per second	Location, in river kilometers
A.......	0	0	---	6.23	109	32.2	142	0	---
B.......	0	6.1	1.6	2.0	98	1.1	142	12.9	288
						1.1	216	12.9	319
						1.1	253		
C[1]	0	7.36	1.6	6.23	109	21.5	142	0	---
						2.12	253		
D.......	0	4.0	1.6	5.0	98	8.0	142	5.5	288
						5.0	216	5.5	319
						8.0	253		
E[1]	0	0	---	6.37	109	0	---	0	---
F1[1]	0	2.83	84	8.5	109	32.6	142	0	---
G1.....	0	0	---	12.5	109	18.4	142	0	---
						8.0	216		
						8.0	253		
F2......	0	0	---	8.5	98	4.6	142	6.1	288
						4.6	216	6.1	319
						4.6	253		
G2.....	0	0	---	8.5	98	4.6	142	6.1	288
						4.6	216	6.1	319
						4.6	253		

[1]Unsteady inflows also were added to model calculations for these flows.

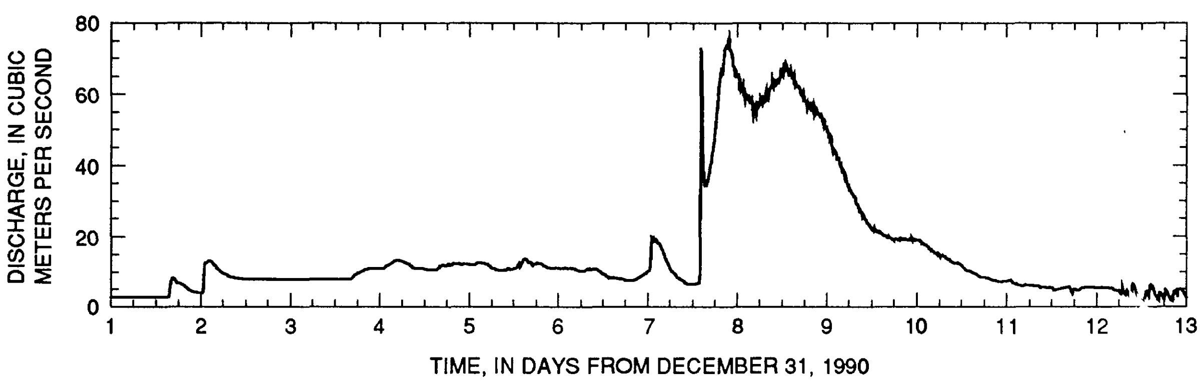

Figure 3. Unsteady discharge from the Little Colorado River during research flow C. Discharge is computed from stage records and the stage-discharge relation developed from stage and discharge measurements at the streamflow-gaging station near Cameron, Arizona.

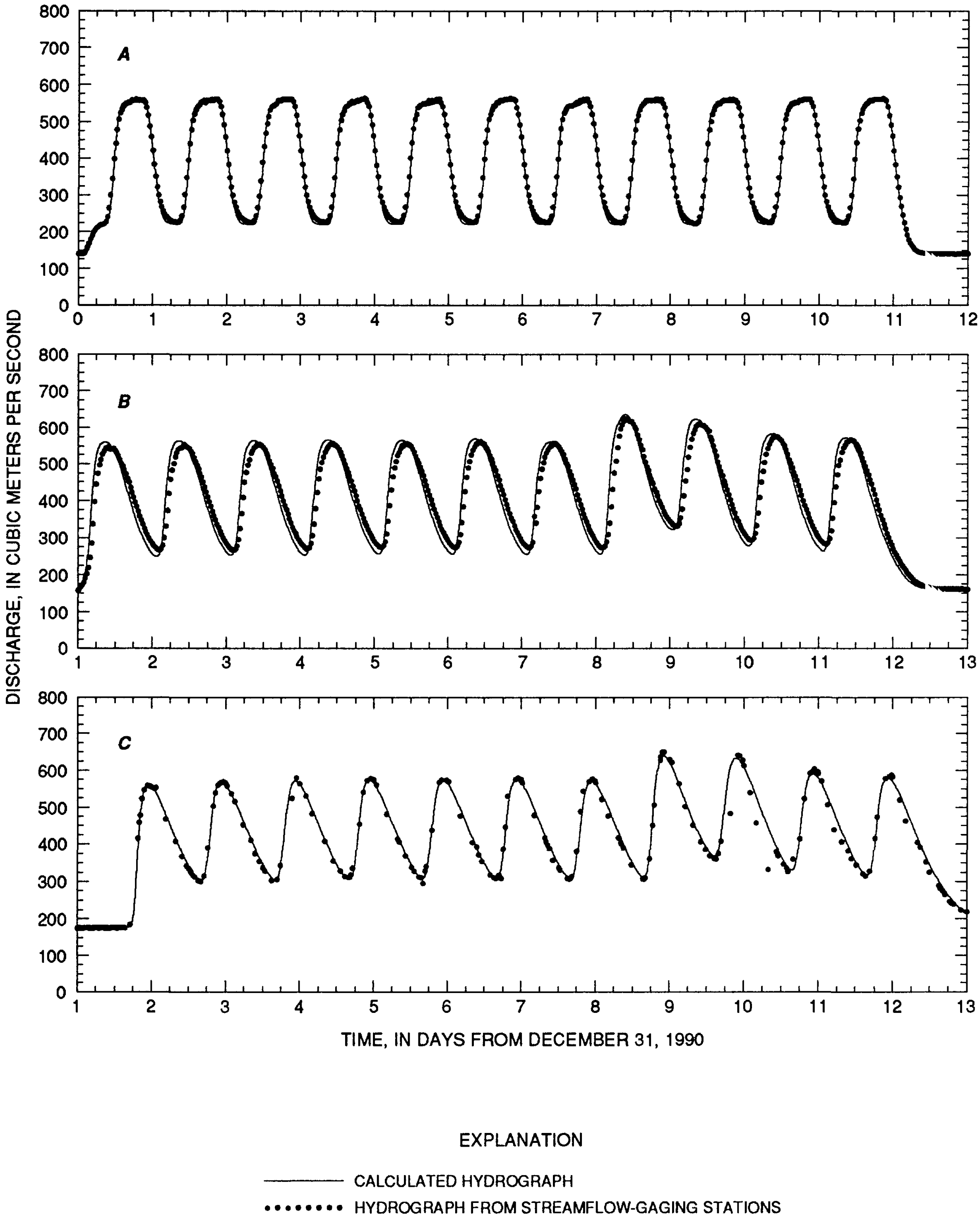

Figure 4. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow C. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River near Grand Canyon (RK 142, RM 88). *C*, Colorado River above National Canyon near Supai (RK 267, RM 166). The streamflow-gaging station records from the remaining gaging stations are either unavailable or contain irregularities suggesting gaging-station malfunction during the flow.

River, therefore, is obscured in the record from the gaging station near Grand Canyon (fig. 6).

During research flow F1, the unsteady inflow from the Paria River was again a single peak of short duration; the peak was of about 63 m^3/s (2,200 ft^3/s; fig. 7). Two significant flows of short duration on the Little Colorado River occurred during research flow F1, which peaked at about 76 m^3/s (2,700 ft^3/s). The effect of this inflow on flow in the Colorado River is evident in the hydrographs computed from the records of the streamflow-gaging stations near Grand Canyon and above National Canyon (fig. 8*C* and *D*).

Data from Stage-Gaging Stations

More detailed stage records reflecting the addition of unsteady inflow were available for research flow C from 29 stage-gaging stations installed by the USGS along the Colorado River. The locations of these stage gages along with other stage gages that have no record for flow C are provided in table 5. The stage gages were installed about 8 km apart between Glen Canyon Dam and Diamond Creek. Discharge is not measured at these sites, and stage-discharge relations have not been developed. Plots of the recorded stage and time, however, clearly indicate time of arrival of peaks and troughs as well as unsteady inflow. Although installation and operation of the stage gages began in 1990, the first research flow for which data generally were available is research flow C; therefore, there is no record from the stage gages for research flows E and F1.

Examination of the stage-gaging station records indicates that unsteady flow was added between RK 88 and 113 (RM 55 and 70; fig. 9). The mouth of the Little Colorado River is at RK 98 (RM 61) on the Colorado River. No additional unsteady inflow during flow C is indicated by these stage-gage records. The gaging station at RK 88 (RM 55) shows no evidence of additional unsteady inflow, but the records from the gaging stations at RK 113 (RM 70) and RK 346 (RM 215) show the

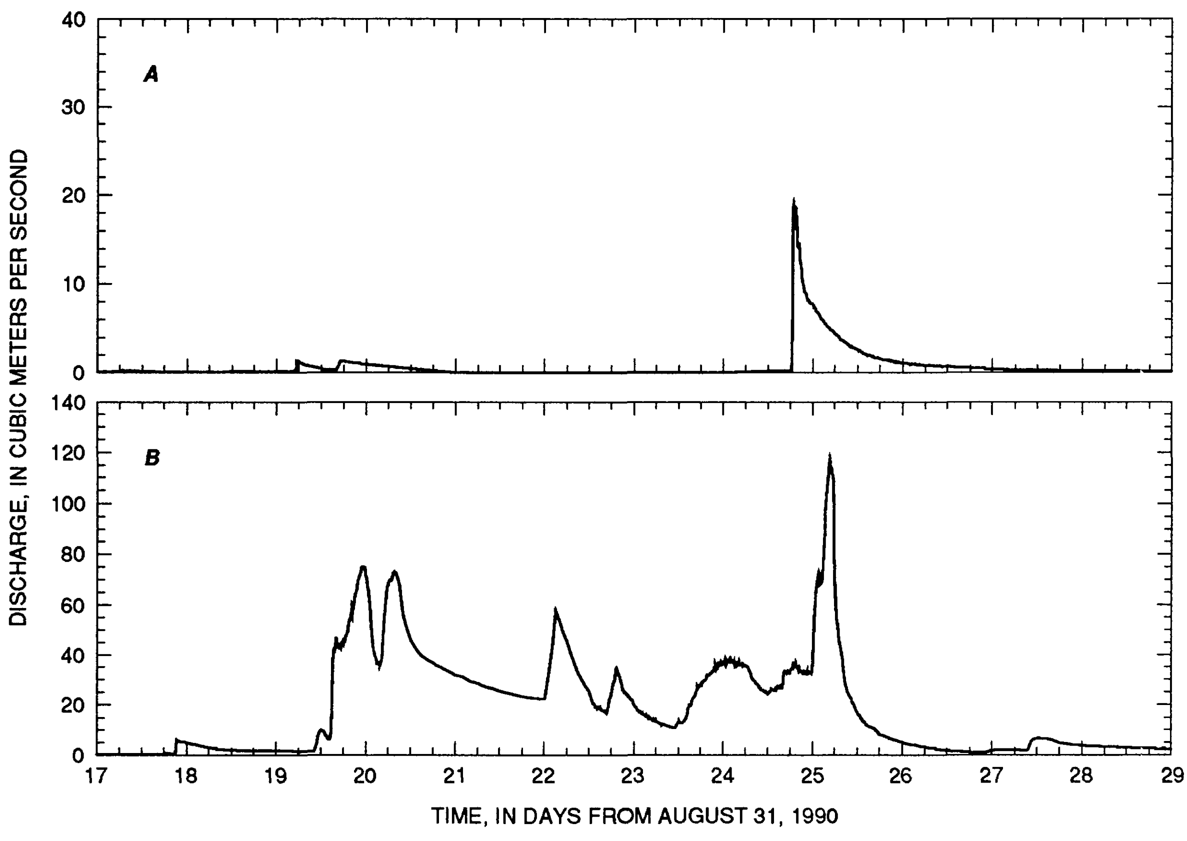

Figure 5. Unsteady tributary discharge during research flow E. *A*, Paria River. *B*, Little Colorado River.

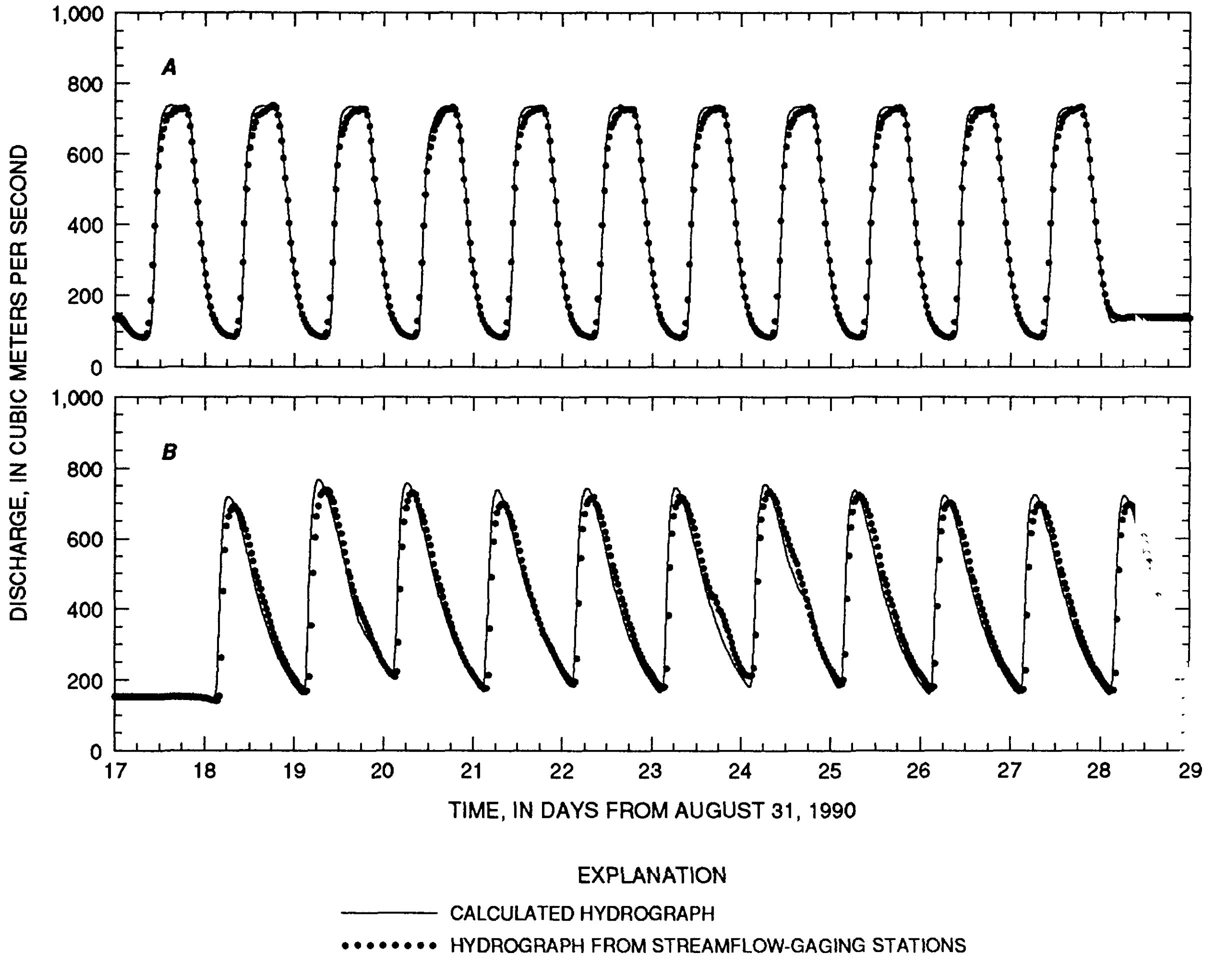

Figure 6. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow E. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River near Grand Canyon (RK 142, RM 88). The streamflow-gaging station records from the remaining gaging stations are either unavailable or contain irregularities suggesting gaging-station malfunction during the flow.

well as from the other stage gages in between) indicates there was no other significant unsteady inflow.

Timing of Unsteady Inflows

The streamflow-gaging station on the Paria River (09382000, Paria River at Lees Ferry, Arizona) is just above the mouth of the Paria River at RK 1.6 on the Colorado River. Inflow from the Paria River, therefore, was determined from data recorded by this gaging station and added directly to the flow calculated by the model 1.6 km downstream from Lees Ferry.

The streamflow-gaging station providing the best available record for flow in the Little Colorado River during the research flows is 09402000, Little Colorado River near Cameron, Arizona, about 72 km (45 mi) above the mouth of the Little Colorado River. The hydrograph computed from the stage recorded at this gaging station was shifted in time to account for the travel time between the gaging station and the mouth of the Little Colorado River. The time shift used was the time shift that gave the best match of the hydrograph calculated by the model at RM 88 with the hydrograph derived from the data recorded by the gaging station near Grand Canyon (09402500, Colorado River near Grand Canyon, Arizona).

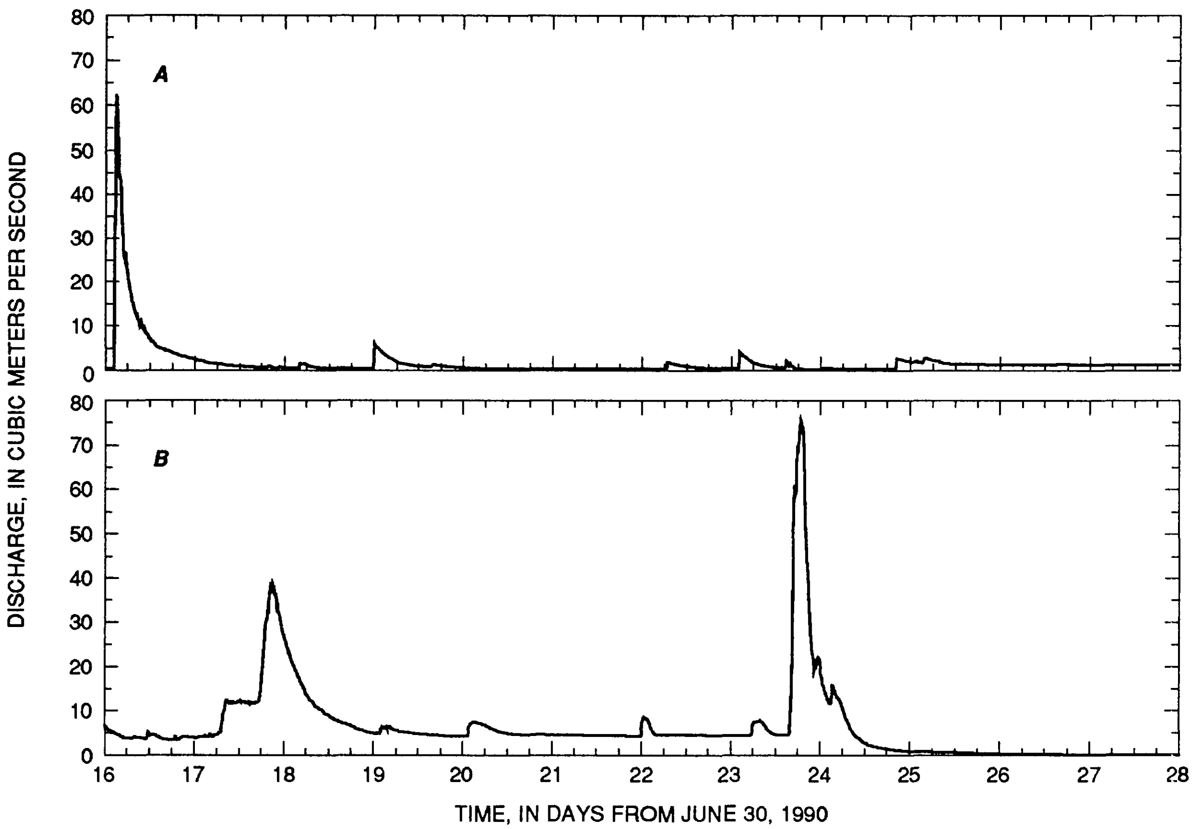

Figure 7. Unsteady tributary discharge during research flow F1. *A*, Paria River. *B*, Little Colorado River.

the gaging station near Grand Canyon (09402500, Colorado River near Grand Canyon, Arizona).

An initial estimate of 7 hours was made for the travel time of the flow between the gaging station near Cameron and the mouth of the Little Colorado River. This estimate was selected as an initial estimate on the basis of the timing of the flow peak recorded at the gaging station near Cameron and the time of arrival of the unsteady flow peak at the gaging station on the Colorado River near Grand Canyon. The travel time of the wave released from the dam between the gaging station on the Colorado River above the Little Colorado River, near Desert View, Arizona (09383100) and the gaging station near Grand Canyon was subtracted from the total travel time of the Little Colorado River flow peak between the gaging stations near Cameron and Grand Canyon.

The difference in time between the arrival of the flow peak at the gaging station near Cameron and the arrival of the wave peak on the Colorado River, which included the Little Colorado River inflow, at the gaging station on the Colorado River near Grand Canyon was about 12 hours during research flows C and F1. The travel time of the research flow wave on the Colorado River between the gaging stations above the Little Colorado River and near Grand Canyon was about 5 hours during research flows C, E, and F1. The travel time for the flow peak between the gaging station near Cameron and the mouth of the Little Colorado River, therefore, was about 7 hours. The model was run with the unsteady flow from the Little Colorado River added at RK 98 (RM 61) with a +7-hour time shift of the discharge of the Little Colorado River computed from the recorded stage and the stage-discharge relation at the gaging station near Cameron.

A comparison of the model-calculated hydrograph at the gaging station near Grand Canyon with the hydrograph computed from the recorded stage and stage-discharge relation at that location showed that the +7-hour time shift did not result in an accurate representation of the time of

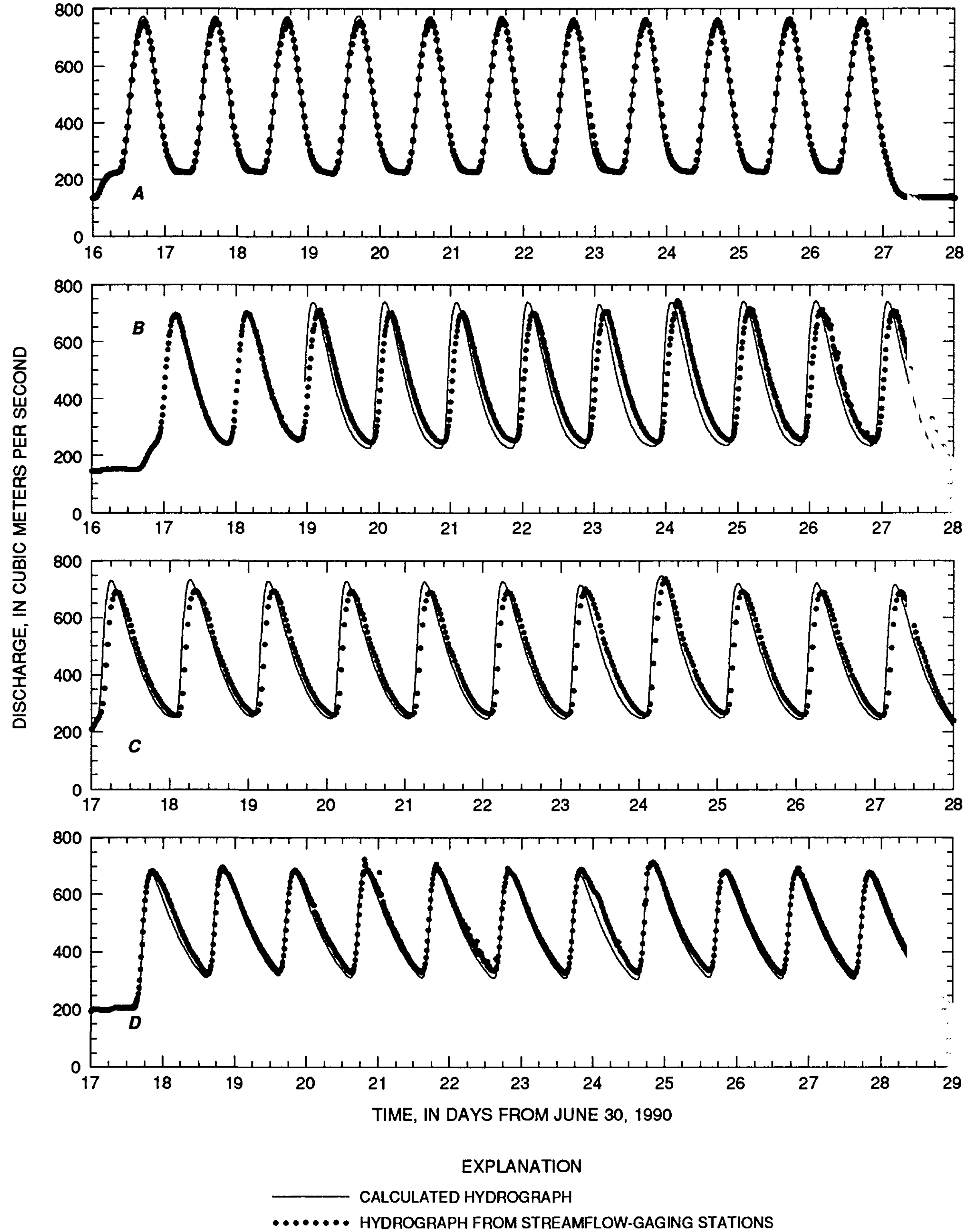

Figure 8. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow F1. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). The record from the streamflow-gaging station above Diamond Creek during this period was unavailable.

Table 5. Stage-gaging stations along the Colorado River between Glen Canyon Dam and Diamond Creek

[RM, river miles upstream or downstream from Lees Ferry]

U.S. Geological Survey gaging-station number	Stage-gage name	Location
09379965	R200–02	6.5 miles above Lees Ferry
09383003	R200–03	At RM 5 below 5 Mile Wash
09383006	R200–04	At RM 10 below 10 Mile Rock
09383009	R200–05	At RM 15 below Sheer Wall Rapid
09383035	R200–06	At RM 20 above North Canyon Rapid
09383040	R200–07	At RM 25 below 24 Mile Rapid
09383050	R200–08	At RM 30 below 29 Mile Rapid
09383060	R200–09	At RM 35 below Nautiloid Canyon
09383070	R200–10	At RM 40 at tramway site
09383075	R200–11	At RM 45 below President Harding Rapid
09383080	R200–12	At RM 50 below 50 Mile Camp
09383090	R200–13	At RM 55 above Kwagunt Rapid
09402350	R200–14	At RM 65 above Lava Canyon Rapid
09402490	R200–15	At RM 70 below Basalt Canyon
09402430	R200–16	At RM 65 above Hance Rapid
09402460	R200–17	At RM 80 above Grapevine Rapid
09403020	R200–18	At RM 90 above Horn Rapid
09403030	R200–18A	At RM 93 above Granite Rapid
09403035	R200–18B	At RM 93.5 below Granite Rapid
09403040	R200–19	At RM 95 above Hermit Rapid
09403045	R200–19A	At RM 95.5 below Hermit Rapid
09403060	R200–20	At RM 98 above Crystal Rapid
09403065	R200–20A	At RM 98.5 below Crystal Rapid
09403100	R200–21	At RM 105 below Ruby Rapid
09403150	R200–22	At RM 110 below 110 Mile Rapid
09403170	R200–23	At RM 115 below Garnet Canyon
09403200	R200–24	At RM 120 above Blacktail Rapid
09403250	R200–25	At RM 125 above Fossil Rapid
09403300	R200–26	At RM 131 above Deubendorff Rapid
09403350	R200–27	At RM 135 above Granite Narrows
09403400	R200–28	At RM 140 below 140 Mile Canyon
09403860	R200–29	At RM 145 above Olo Canyon
09403870	R200–30	At RM 150 above Upset Rapid
09403880	R200–31	At RM 155 below Sinyala Rapid
09404117	R200–32	At RM 160, 3 miles below Havasu Creek
09404119	R200–32A	At RM 165.5 above National Canyon
09404130	R200–33	At RM 170 above Stairway Canyon
09404135	R200–34	At RM 175 below Cove Canyon
09404140	R200–35	At RM 179 above Lava Falls Rapid
09404145	R200–36	At RM 185 above 185 Mile Rapid
09404150	R200–37	At RM 190, 2 miles below Whitmore Rapid
09404155	R200–38	At RM 195 below 194 Mile Canyon
09404165	R200–39	At RM 200 below Parashant Wash
09404170	R200–40	At RM 205 above 205 Mile Rapid
09404180	R200–41	At RM 210 below Granite Park
09404185	R200–42	At RM 215 above Three Springs Canyon
09404190	R200–43	At RM 220 above 220 Mile Canyon

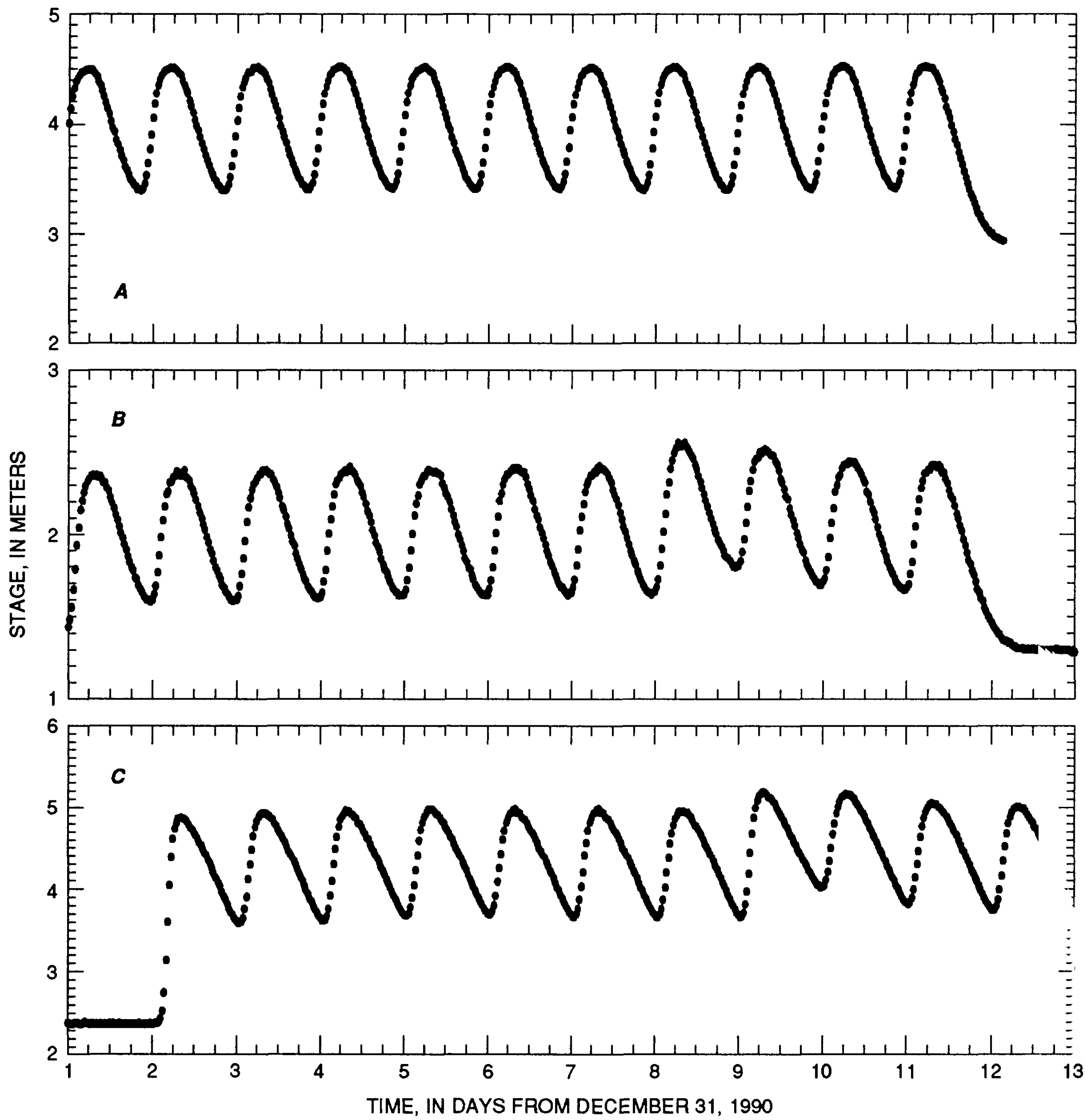

Figure 9. Stage recorded during research flow C at stage-gaging stations. *A*, R200-13 (RK 88, RM 55). *B*, R200-15 (RK 113, RM 70). *C*, R200-42 (RK 346, RM 215). R200-42 is the stage-gaging station farthest downstream from the dam that recorded data during research flow C.

arrival of the unsteady flow peak at the gaging station near Grand Canyon. An estimate of the additional time delay required to obtain a better match between the two hydrographs then was made and added to the adjusted flow data from the gaging station at Little Colorado River near Cameron. The time shift that achieved the best match in each case was +9.12 hours. This adjustment is based on single flow events in the Little Colorado River during research flows C and F1 that had peak discharges of about 76 m^3/s (2,700 ft^3/s).

The same adjustment (+9.12 hours) was applied to the data from the gaging station near Cameron for research flow E because the record from the gaging station near Grand Canyon does not clearly indicate the arrival of the flow peak from the Little Colorado River during flow E. The +9.12 hours, therefore, was the best estimate that could be made of the necessary time shift for research flow E. The addition of the unsteady discharge from the Paria and Little Colorado Rivers to the model calculations for reach flows C, E, and F1 resulted in good agreement between the calculated hydrographs and the hydrographs computed from the stage record at the downstream gaging stations as shown in figures 4, 6, and 8, respectively.

COMPARISON OF MODEL-CALCULATED HYDROGRAPHS WITH COMPUTED HYDROGRAPHS

The hydrographs calculated by the model and hydrographs computed from the data recorded by the streamflow-gaging stations are shown in figs. 10–18 for the first four days of research flows A, B, C, D, E, F1, G1, F2, and G2, respectively. The hydrographs calculated for the 5 streamflow-gaging stations and 33 beach study sites for each of the 9 unsteady research flows also are available in electronic form through the USGS. Information concerning how to access the hydrographs can be obtained by contacting the District Chief, Water Resources Division, Tucson, Arizona.

An analysis of model results was performed by comparing data from the five streamflow-gaging stations along the Colorado River with the model-calculated results. Wave characteristics that were compared included rate of increase and decrease of discharge, peak and trough discharges, and wave travel time (determined by tracking the advance of the wave trough) as functions of distance downstream. Also, the average absolute error of the wave travel time over 90 percent of the wave, excluding just the peaks and troughs, was calculated as a measure of model accuracy over most of the wave (table 6). Periods with only steady inflow were used to compare model results with hydrographs computed from gaging-station records for research flows that had unsteady inflows (C, E, and F1).

In some cases, gaging-station records were unavailable, and in other cases, the records contained irregularities that appear to be caused by gaging-station malfunction during part of all of the research flow. These records, therefore, were not used in the analysis of model results. Cases where records were missing or may be in error are noted in table 6. For research flow E, data are available only from the gaging stations at Lees Ferry and Grand Canyon. Estimates of inflow added to the model calculation and the analysis of the research flows are based on the available records.

Before the calculated hydrographs were compared to the hydrographs computed from the streamflow data from the gaging stations above National Canyon and Diamond Creek, a correction was applied to this streamflow data to ensure that mass was conserved between the gaging stations. A detailed discussion of the reasons for applying this correction and its development is provided by Wiele and Smith (1995). In the calculations made for this report, this correction was applied to discharge computed from data recorded at these gaging stations during each of the flows except for the data from the gaging station above National Canyon for research flows F1 and G1. A correction of the data from the gaging station above National Canyon was not necessary for research flows F1 and G1. Flows F1 and G1 are the only research flows in 1990 for which a gaging-station record for National Canyon is available.

The first test of the ability of the model to predict accurately the evolution of the wave as it travels downstream is a comparison of the rates of increase and decrease in discharge calculated by the model with the rates determined from the gaging-station records. These rates are measures of the wave shape and reflect the steepening of the rising limb of the wave as it moves downstream after its release from the dam. The model accurately predicts the rates of decrease in discharge (negative values) compared to the rates calculated from each of the hydrographs derived from gaging-station records (fig. 19). The model, however, tends to produce a higher rate of increase in discharge than the rates calculated from stage-discharge relations and the stage records at the gaging stations between the dam and the gaging station near Grand Canyon for some of the flows.

The second test used to evaluate the model results is a comparison of the peak and trough discharges calculated by the model with the discharges computed from the gaging-station records as a function of distance upstream and downstream from Lees Ferry (fig. 20). For the

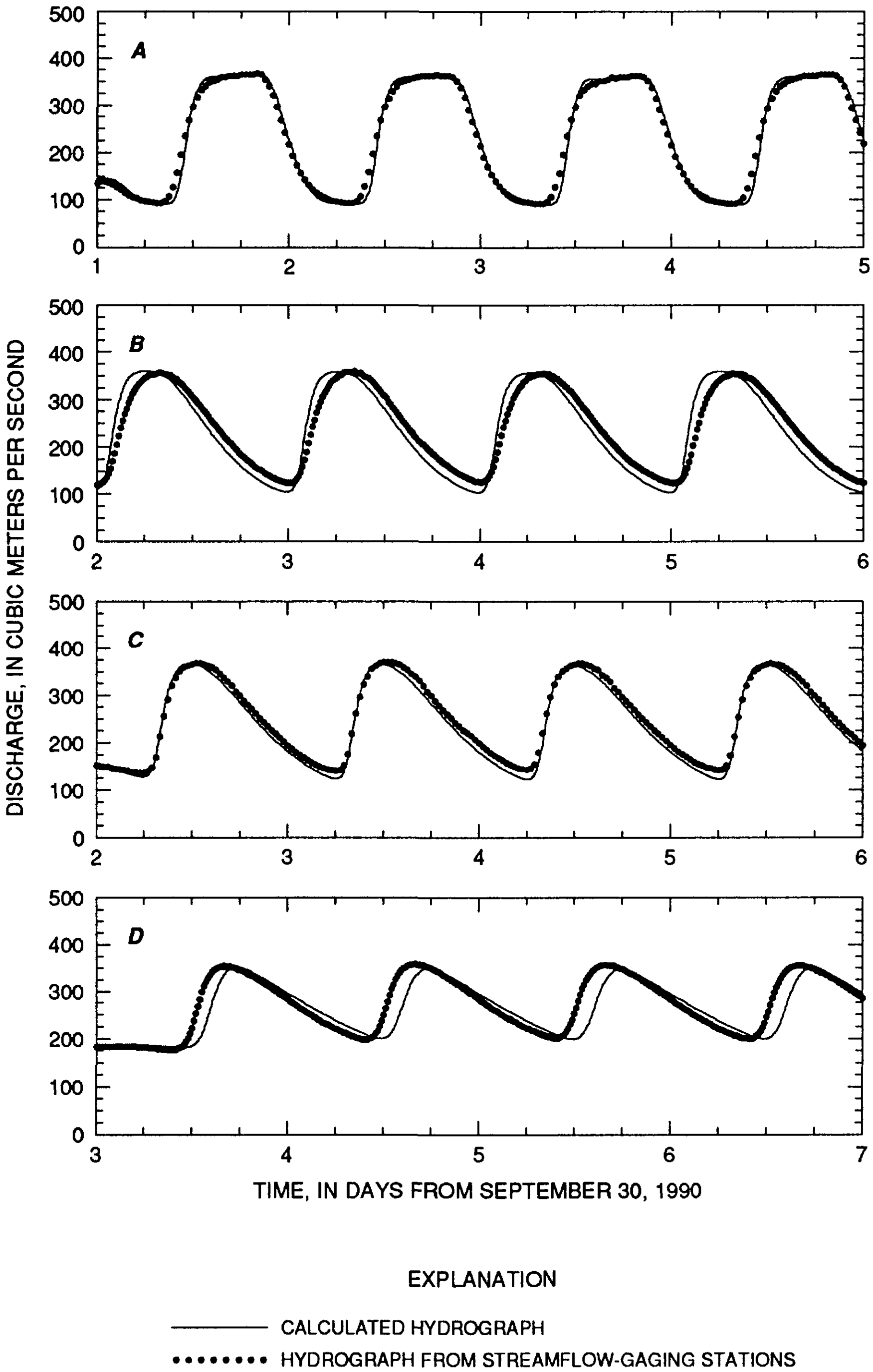

Figure 10. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow A. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above Diamond Creek near Peach Springs (RK 362, RM 225). No record was available for the gage above National Canyon near Supai (RK 267, RM 166) during flow A. The hydrographs are positioned to show the rise of the first wave following the steady flow.

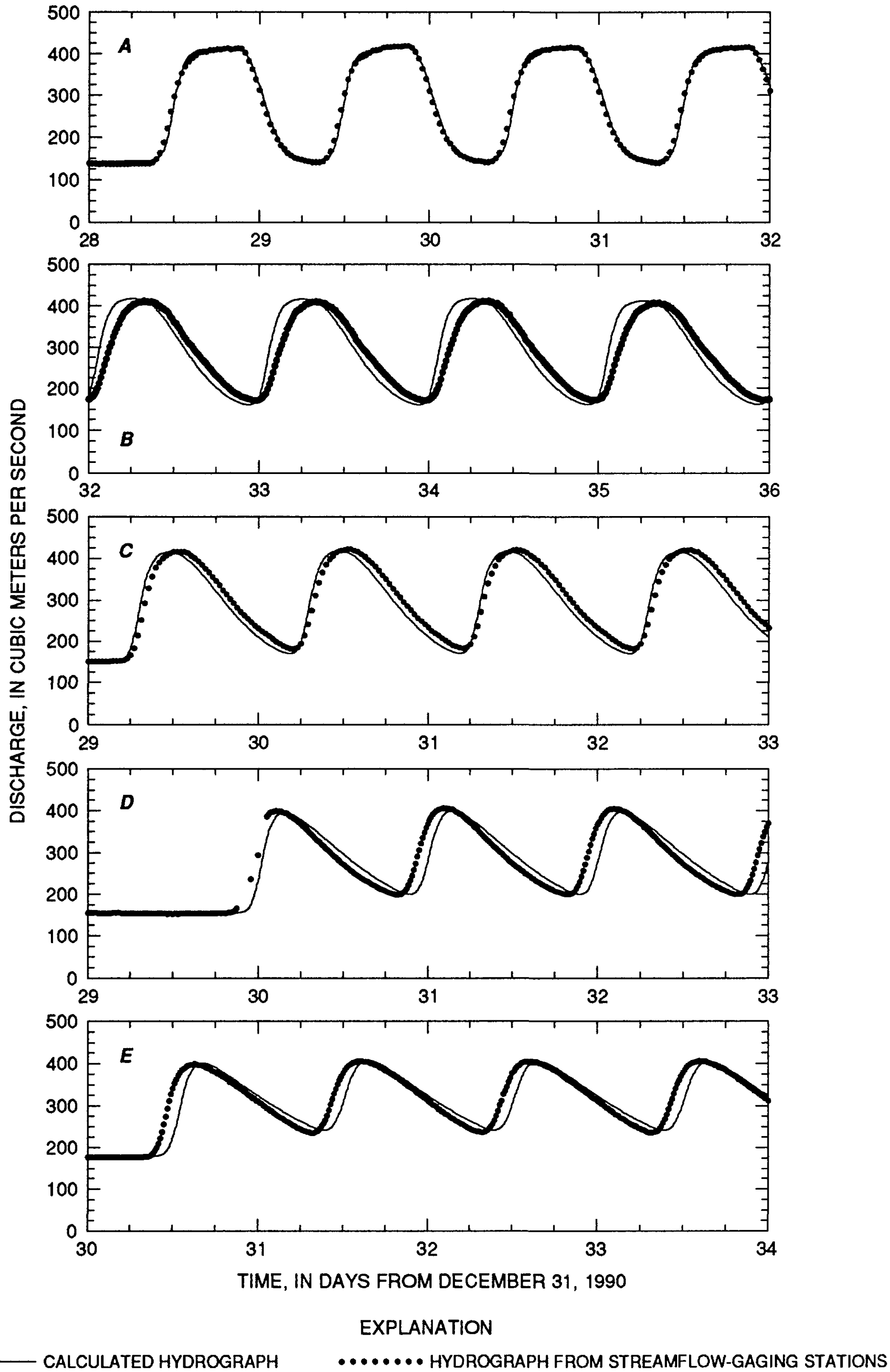

Figure 11. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow B. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). *E*, Colorado River above Diamond Creek near Peach Springs (RK 362, RM 225). The hydrographs are positioned to show the rise of the first wave following the steady flow, with the exception of *B* where the streamflow record is incomplete.

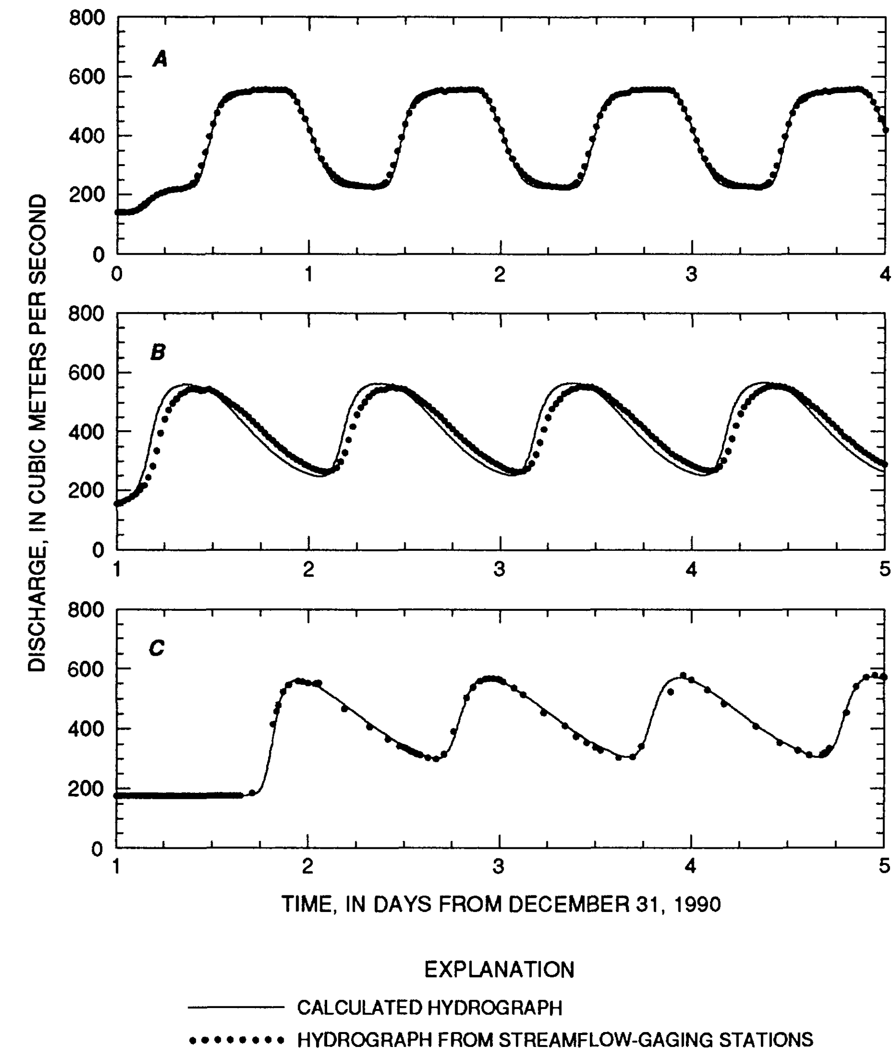

Figure 12. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow C. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River near Grand Canyon (RK 142, RM 88). *C*, Colorado River above National Canyon near Supai (RK 267, RM 166). The records from the remaining gaging stations are either unavailable or contain irregularities that indicate gaging-station malfunction during the flow. The hydrographs are positioned to show the rise of the first wave following the steady flow.

research flows with unsteady inflow, periods with only steady inflow were chosen for the comparison. The waves released from the dam spread as they move downstream and caused the peak discharge to decrease and the trough discharge to increase. The increase in trough discharge is a result of the repeated wave release. Steady tributary inflows cause step increases in peak and trough discharges (fig. 20).

In most cases, the peak and trough discharges calculated by the model agree well with the discharges computed from the gaging-station records. The two cases with the largest deviations between the calculated discharge and the discharge computed from the gaging-station record are at the gaging stations near Grand Canyon (RK 142) during research flow E and above National Canyon (RK 267) during research flow G2. In both cases, the difference is in the magnitude of the peak discharge calculated by the model and the peak discharge computed from the gaging-station record, and the difference is less than 10 percent of

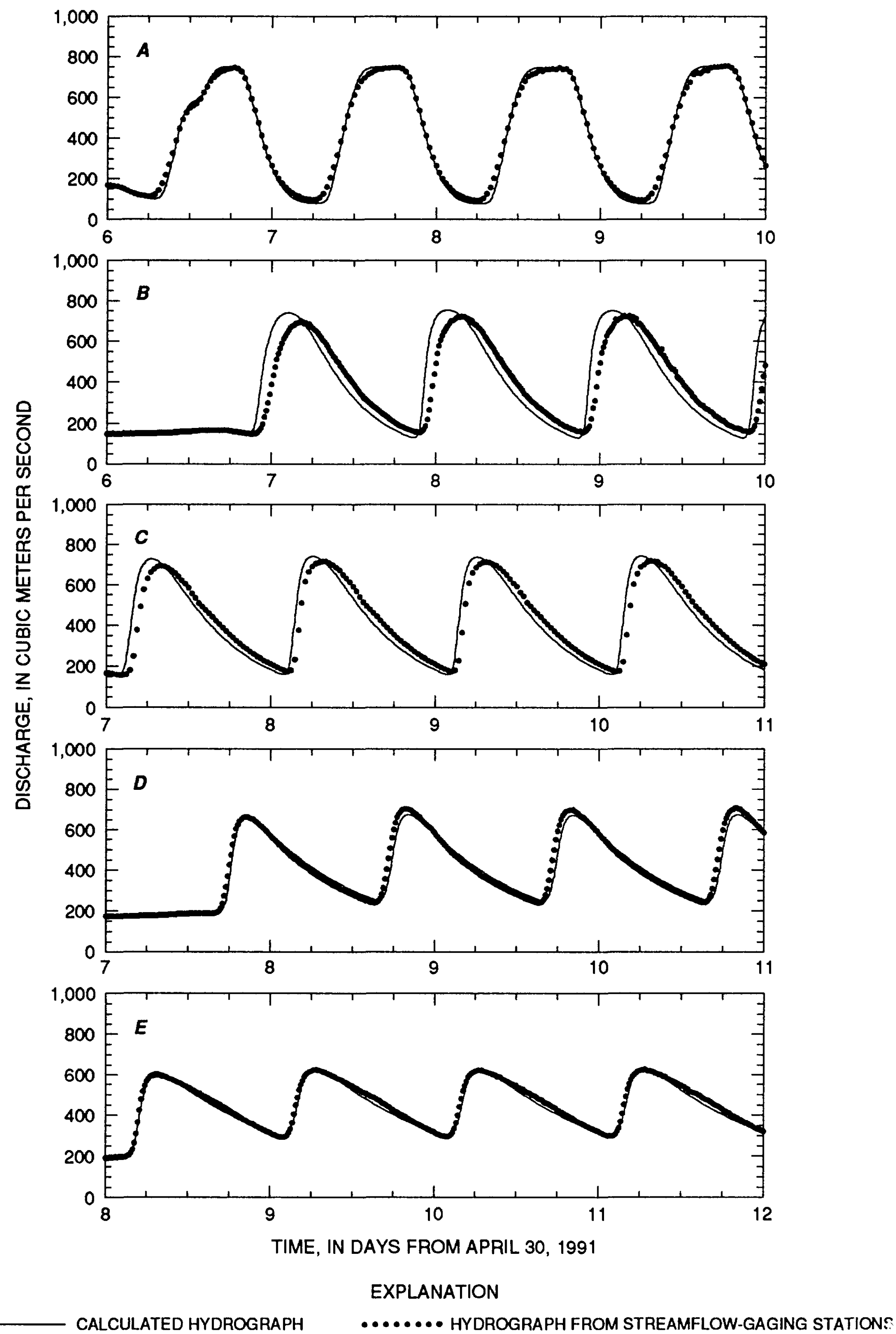

Figure 13. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow D. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). *E*, Colorado River above Diamond Creek near Peach Springs (RK 362, RM 225). The hydrographs are positioned to show the rise of the first wave following the steady flow.

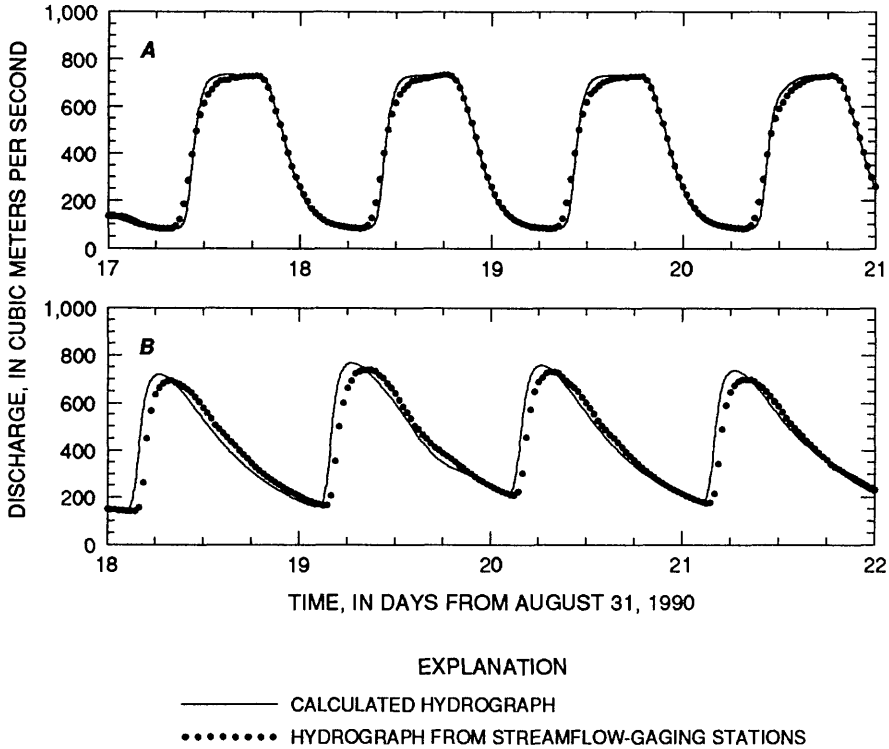

Figure 14. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow E. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River near Grand Canyon (RK 142, RM 88). The records from the remaining gaging stations either are unavailable or contain irregularities that indicate gaging-station malfunction during the flow. The hydrographs are positioned to show the rise of the first wave following the steady flow.

Table 6. Average absolute error and percent error of the calculated time for a given discharge at five streamflow-gaging stations downstream from Glen Canyon Dam

[Numbers in parentheses are percent error and were calculated by dividing the average absolute error, in hours, by the travel time of the first trough from Glen Canyon Dam to the gaging-station location, in hours, and multiplying by 100. Dashes indicate that gaging-station records are unavailable or may be in error]

Gaging-station location	Distance downstream from Lees Ferry, in river kilometers	Average absolute error, in hours, for specified research flow								
		A	B	C	D	E	F1	G1	F2	G2
Lees Ferry..............	0	0.53 (9.0)	0.31 (4.1)	0.35 (6.4)	0.23 (4.8)	0.33 (4.1)	0.30 (5.5)	0.38 (4.2)	0.36 (5.5)	0.36 (5.5)
Above the Little Colorado River......	98	1.10 (4.9)	1.38 (6.7)	---	1.38 (6.8)	---	1.76 (8.3)	1.96 (8.8)	1.69 (8.6)	1.69 (9.2)
Near Grand Canyon..................	142	.36 (1.3)	.82 (2.8)	1.18 (5.0)	1.24 (4.9)	.98 (3.6)	1.29 (5.0)	1.51 (5.5)	1.56 (6.4)	1.56 (6.8)
Above National Canyon..................	267	---	1.6 (3.7)	.78 (2.1)	.82 (2.2)	---	.48 (1.2)	.36 (.9)	.43 (1.2)	.43 (1.2)
Above Diamond Creek.....................	362	1.71 (3.1)	1.24 (2.2)	---	.86 (1.8)	---	---	---	2.01 (4.2)	2.01 (4.4)

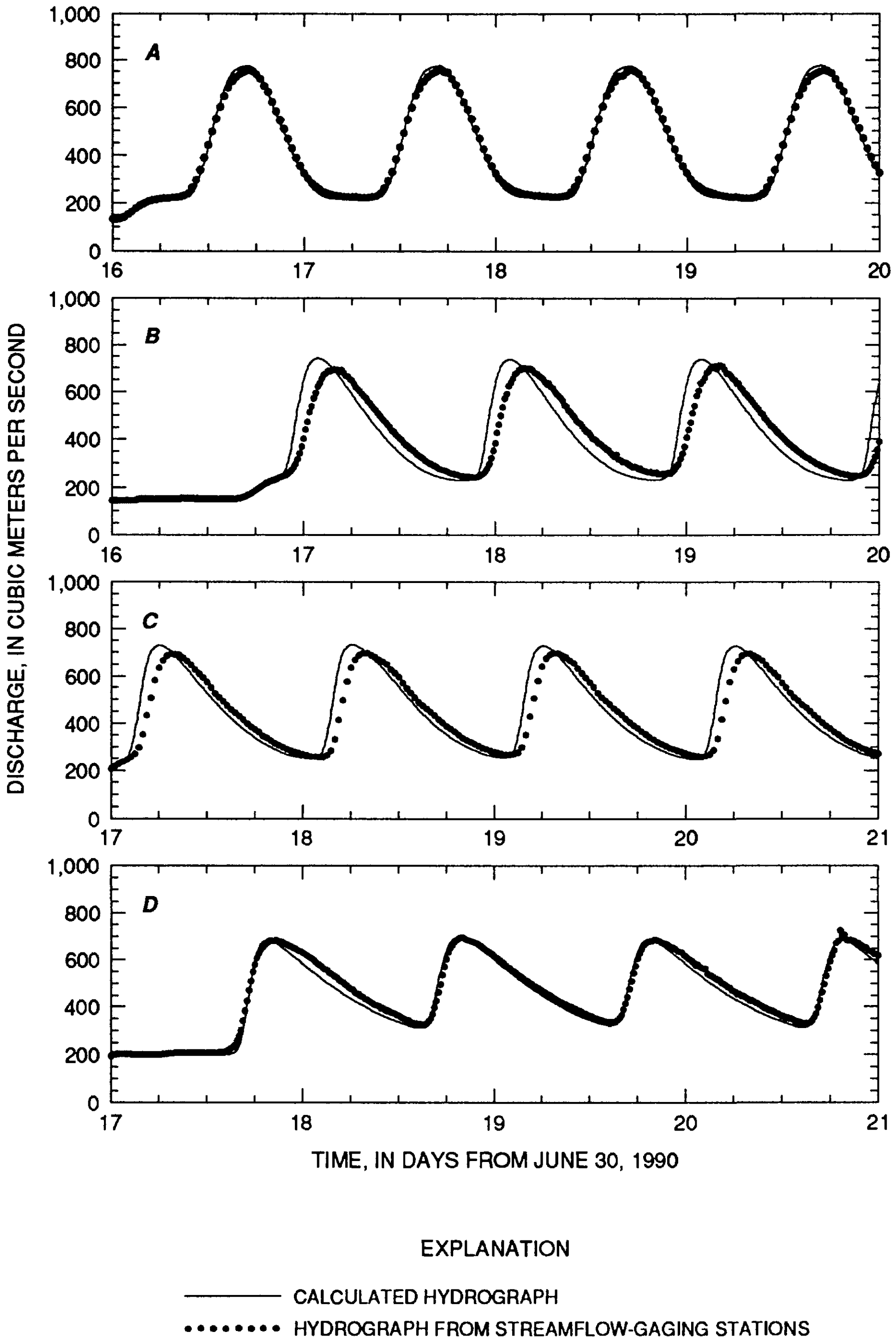

Figure 15. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow F1. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). The record from the streamflow-gaging station above Diamond Creek during this flow was unavailable. The hydrographs are positioned to show the rise of the first wave following the steady flow.

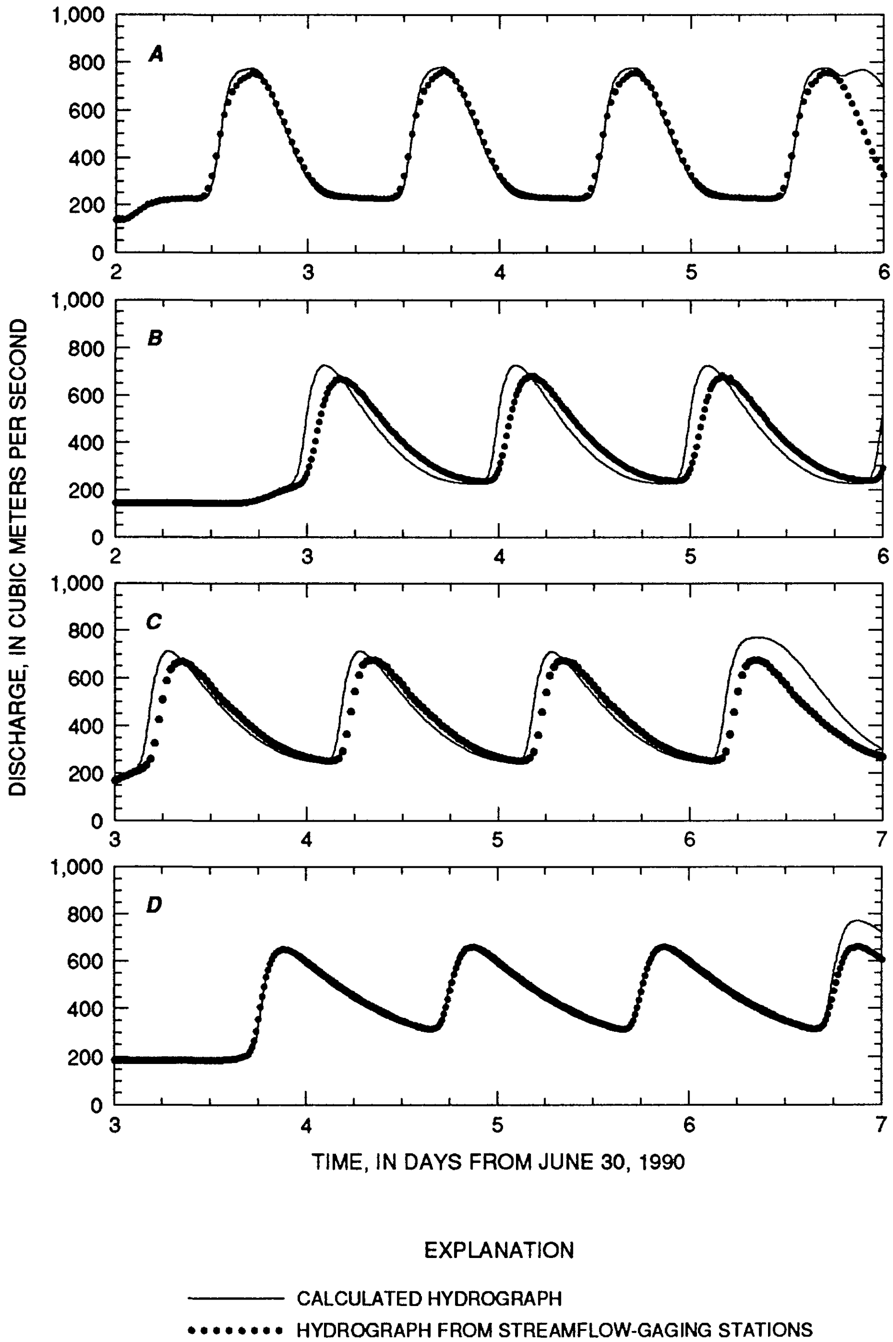

Figure 16. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow G1. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). The record from the streamflow-gaging station above Diamond Creek during this flow was unavailable. The hydrographs are positioned to show the rise of the first wave following the steady flow.

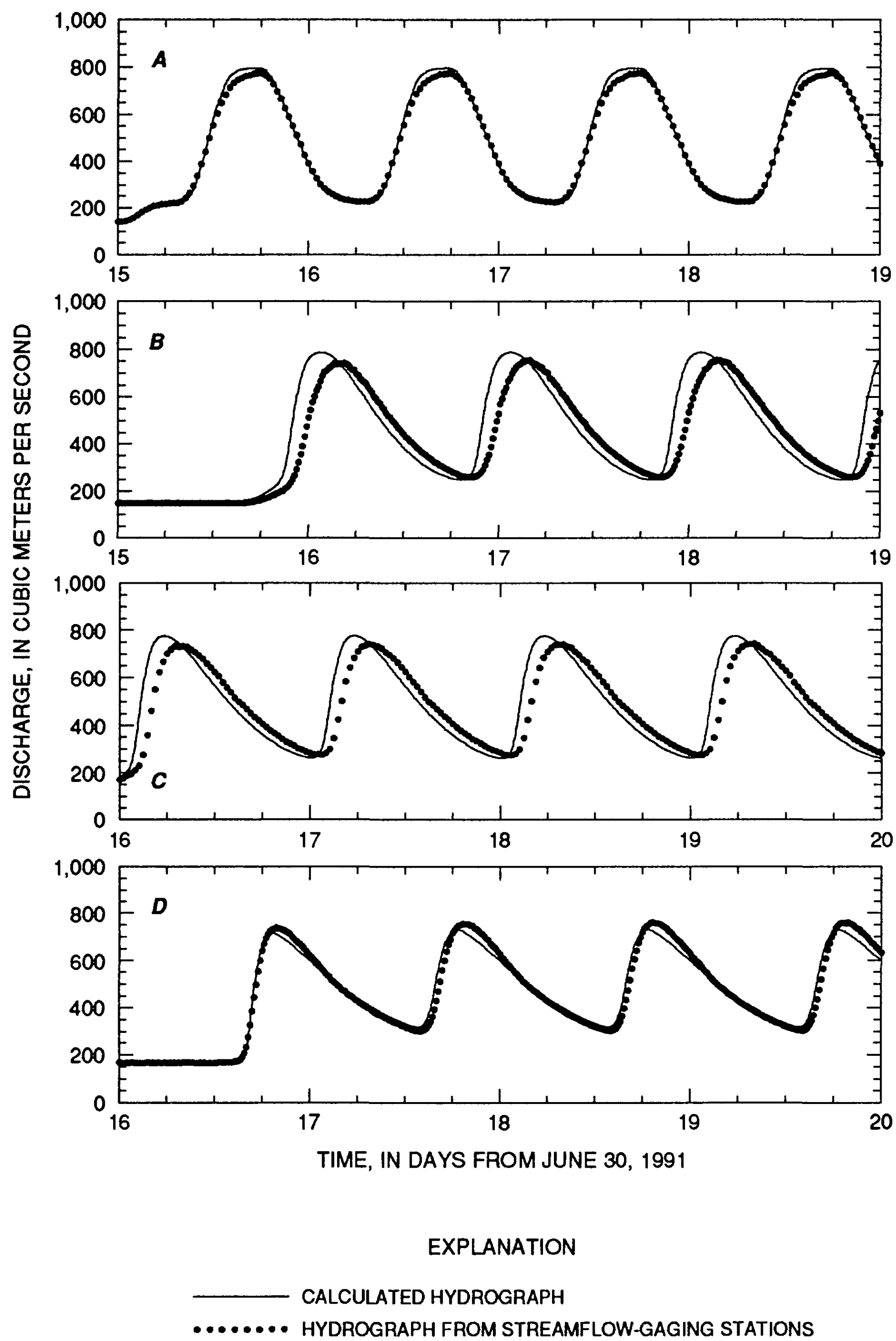

Figure 17. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow F2. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Granc' Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). The hydrographs are positioned to show the rise of the first wave following the steady flow.

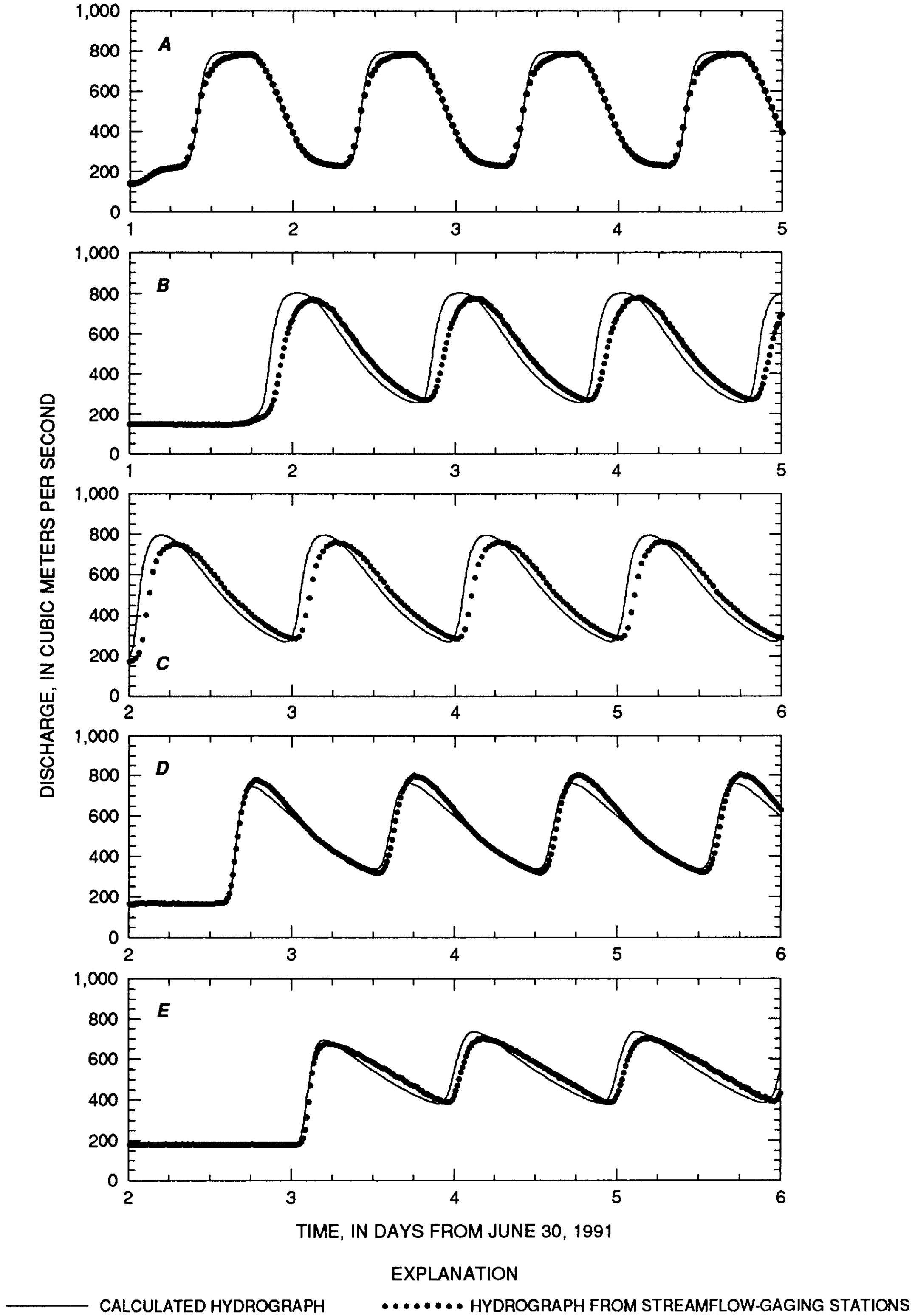

Figure 18. Calculated hydrographs and hydrographs determined from stage records and the stage-discharge relations at streamflow-gaging stations for research flow G2. *A*, Colorado River at Lees Ferry (RK 0). *B*, Colorado River above Little Colorado River near Desert View (RK 98, RM 61). *C*, Colorado River near Grand Canyon (RK 142, RM 88). *D*, Colorado River above National Canyon near Supai (RK 267, RM 166). *E*, Colorado River above Diamond Creek near Peach Springs (RK 362, RM 225). The hydrographs are positioned to show the rise of the first wave following the steady flow.

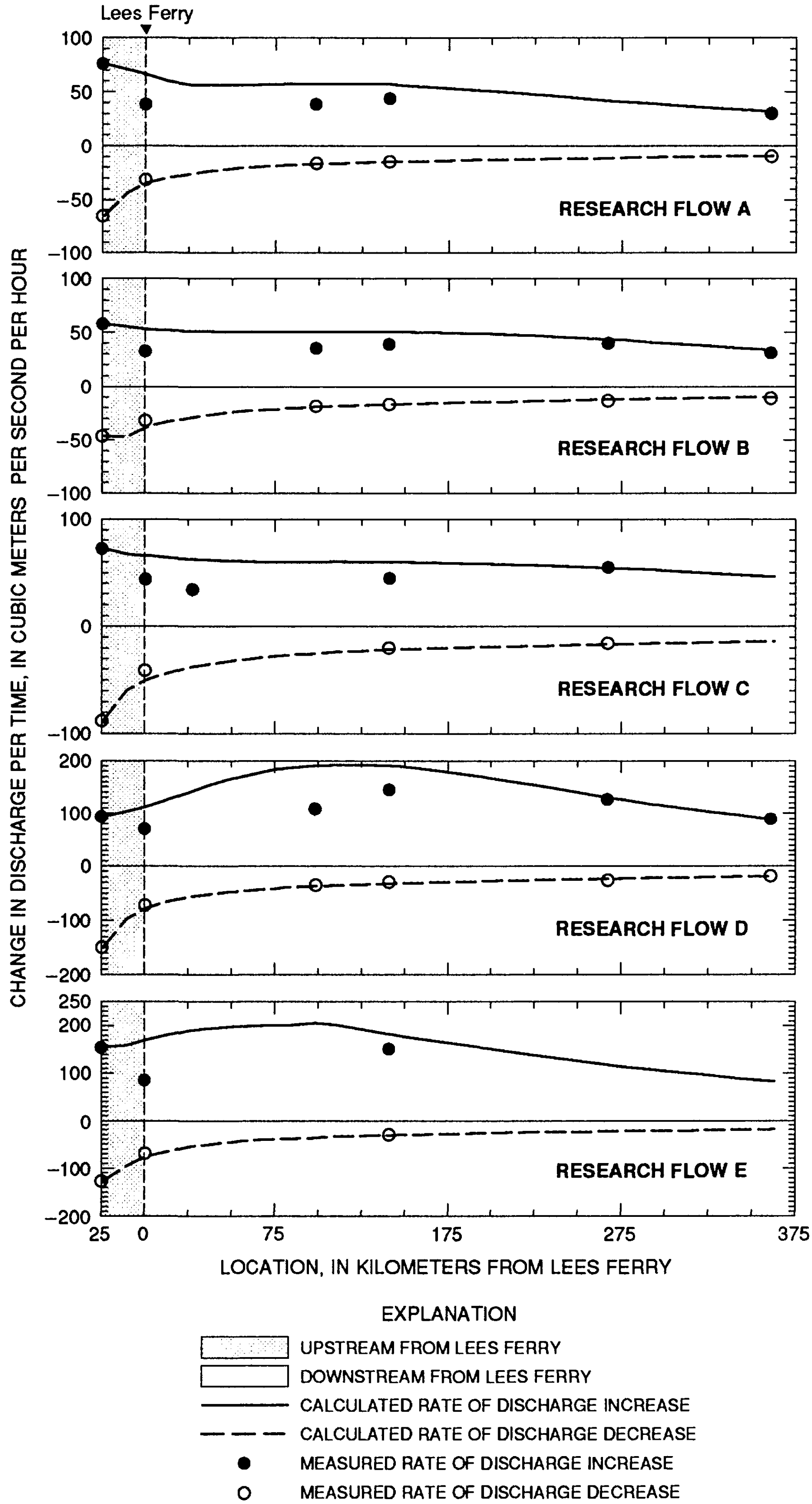

Figure 19. Calculated and measured rates of discharge increase (positive values) and decrease (negative values) as a function of distance downstream for research flows A–G2. The rates were determined from the middle 90 percent of the wave height.

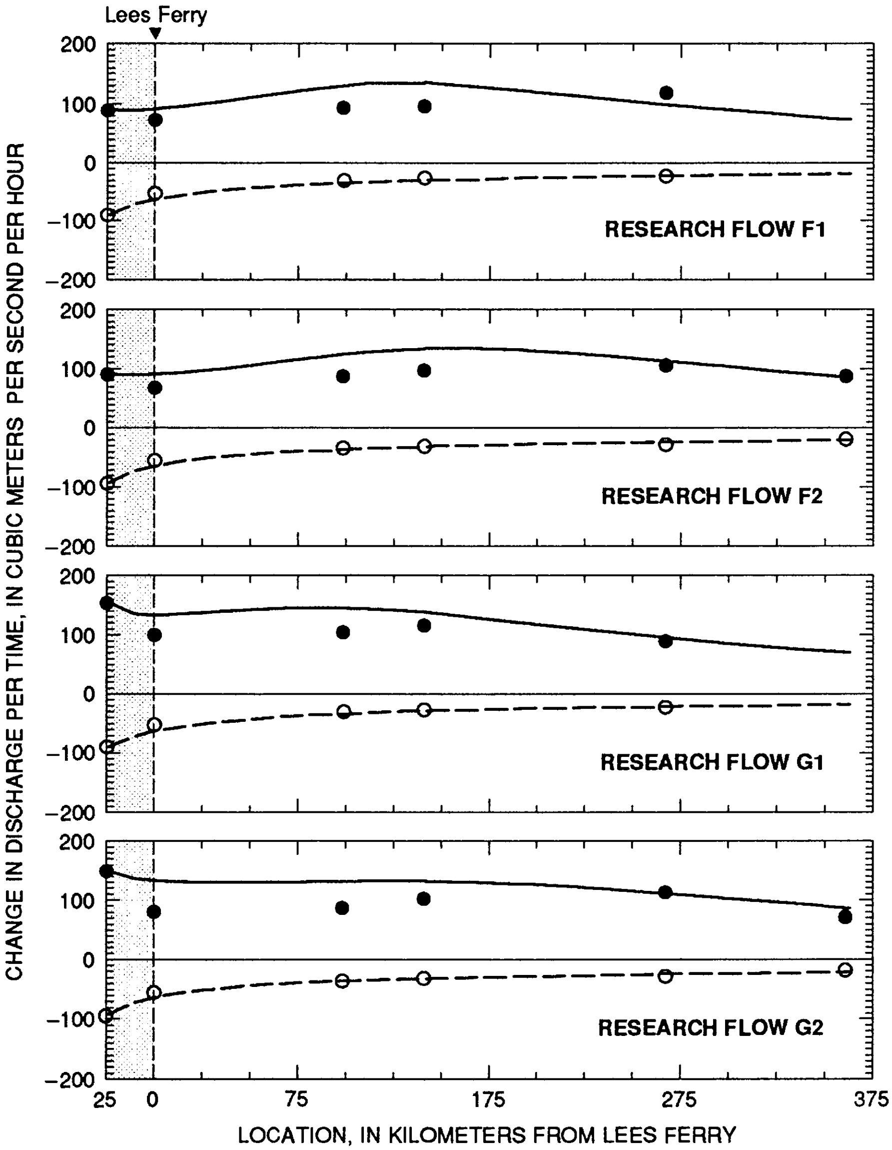

Figure 19. Continued.

the peak discharge computed from the gaging-station record.

Finally, the model prediction of the wave travel time after its release from the dam to each of the five streamflow-gaging stations is compared to the travel time of the wave as recorded at the gaging stations. The travel time was determined by taking the difference between the time of release of the lowest point of the first trough from the dam (as recorded by the gaging station just below the dam) and the arrival time of the same point at each of the gaging stations farther downstream. The model results agree well with the travel times obtained from the available gaging-station records (fig. 21).

The average absolute error in the computed arrival time of the wave over the wave period also was calculated for each flow at each gaging station (fig. 21 and table 6). This value indicates the accuracy with which the model predicts the arrival of a complete wave. The average absolute error is calculated by (1) summing the difference between the calculated time for a given discharge on a nondimensionalized hydrograph and the corresponding time on a hydrograph derived from stage records at the gaging station over a 24-hour period and (2) dividing by the number of samples. (The upper and lower 5 percent of the wave was not used in this calculation). The normalized discharge

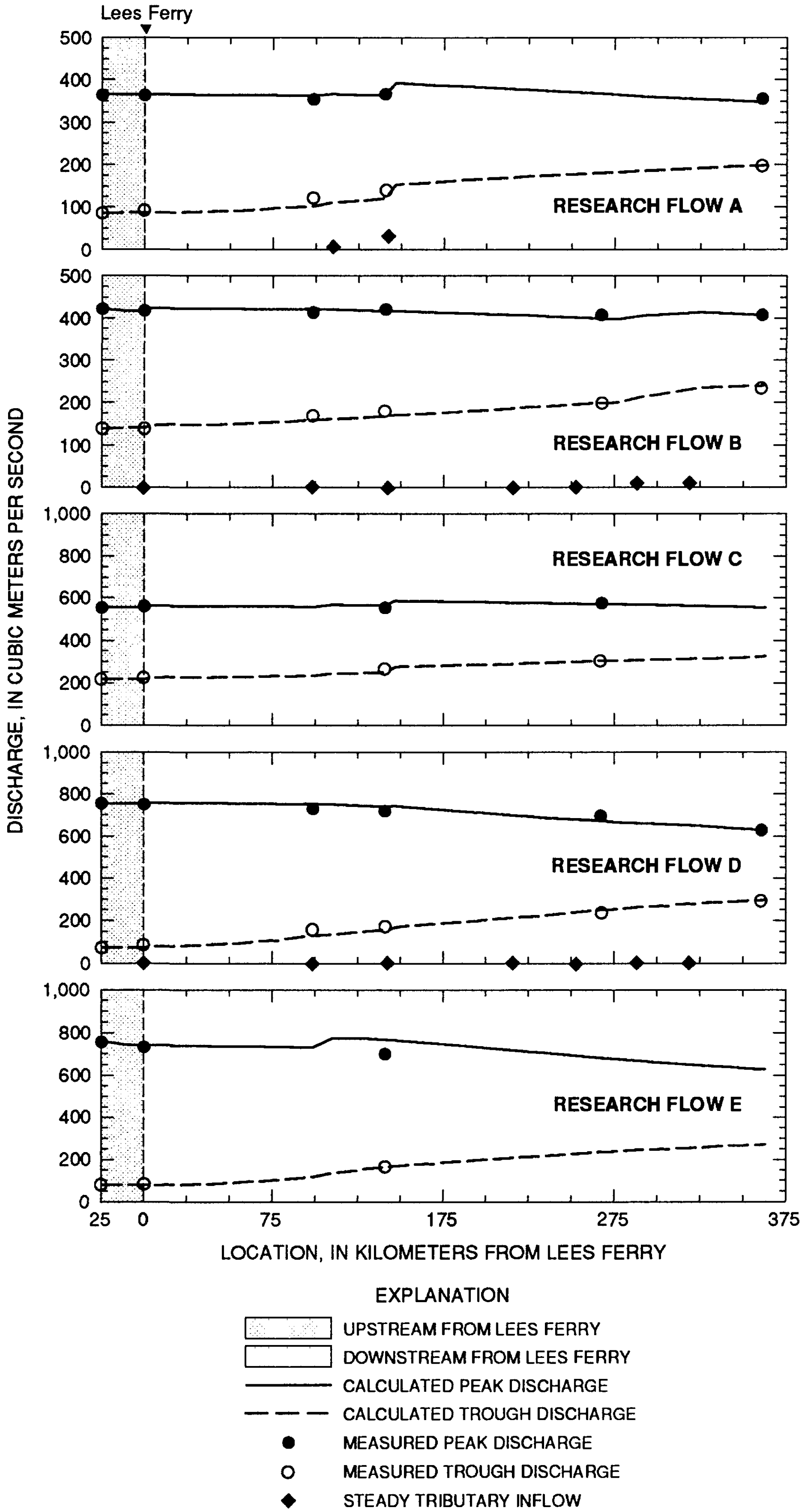

Figure 20. Calculated and measured peak and trough discharges as a function of distance downstream for research flows A–G2.

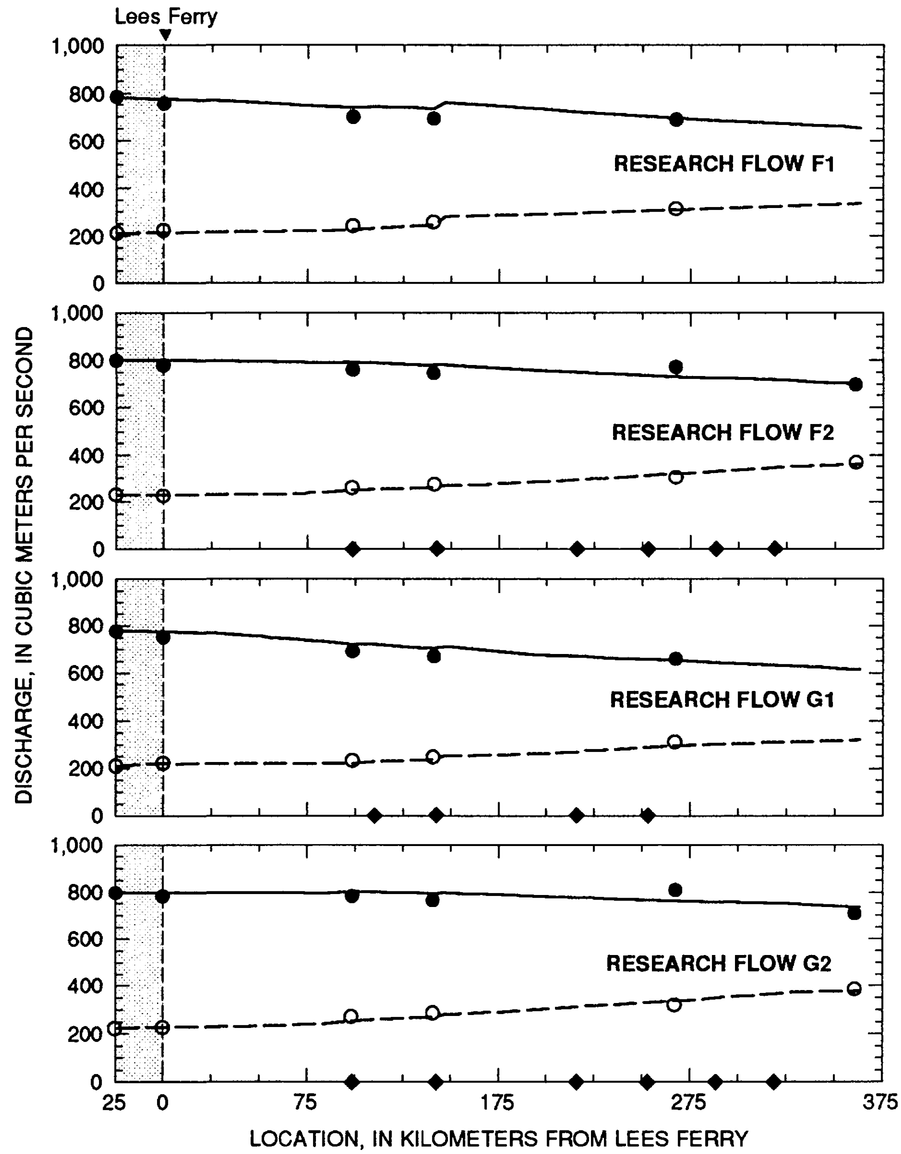

Figure 20. Continued.

was used to avoid dependence on stage-discharge relations (Wiele and Smith, 1995).

SUMMARY AND CONCLUSIONS

Hydrographs have been calculated at 5 streamflow-gaging stations and the 33 beach-study sites on the Colorado River for each of 9 unsteady releases from Glen Canyon Dam. The results of the model have been compared to the hydrographs computed from recorded stage and the associated stage-discharge relations developed for each of the five gaging stations where records are available. These comparisons show that the model accurately predicts the changes in the shape of the wave as it moves downstream, as well as the decrease in peak discharge and increase in trough discharge resulting from the wave spreading as it moves downstream. The agreement in the peak and trough discharges between the model-calculated hydrographs and hydrographs computed from the streamflow-gaging stations records also indicates steady and unsteady inflows were accurately added. The greatest average absolute error in the model-calculated wave travel time was 2.01 hours at the streamflow-gaging station above Diamond Creek for research flows F2 and G2. This error was

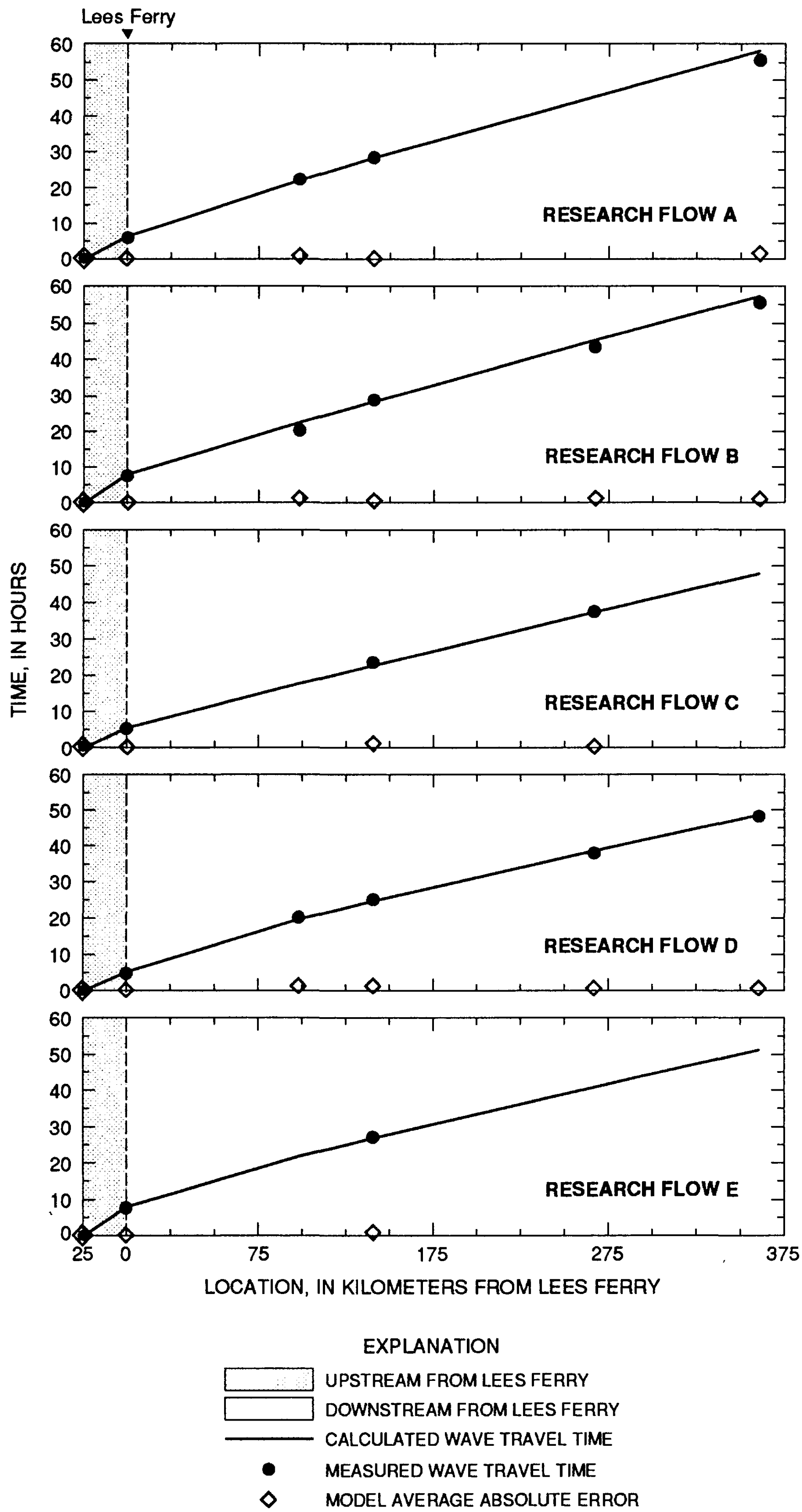

Figure 21. Calculated and measured wave travel time from Glen Canyon Dam, and the model average absolute error for research flows A–G2.

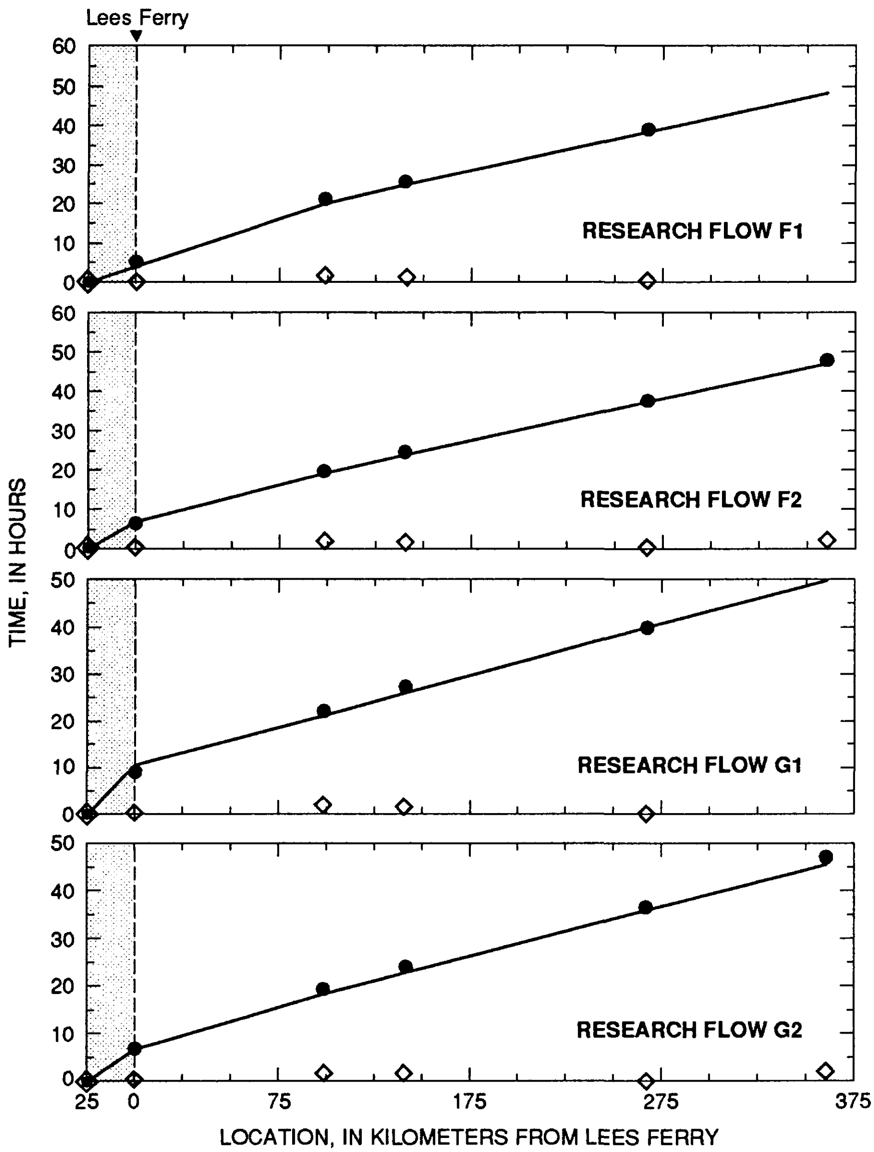

Figure 21. Continued.

less than 5 percent of the total time (about 47 hours) for the wave to travel 386 km downstream from Glen Canyon Dam to Diamond Creek. The hydrographs calculated by the one-dimensional unsteady flow model, therefore, are in good agreement with the hydrographs computed from gaging-station records.

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