PRELIMINARY DRAFT--SUBJECT TO REVISION AZ12100-769 3-30-92.2

TRAVELTIME AND LONGITUDINAL DISPERSION AT STEADY AND UNSTEADY FLOWS, COLORADO RIVER, GLEN CANYON DAM TO LAKE MEAD

by Julia B. Graf

U.S. Geological Survey

Open-File Report 92-____

Prepared in cooperation with the

U.S. BUREAU OF RECLAMATION

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Tucson, Arizona
March 1992

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Multiply metric unit	*By*	*To obtain inch-pound unit*
meter (m)	3.281	foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
kilometer (km)	0.6214	mile
kilogram (kg)	2.205	pound

TRAVELTIME AND LONGITUDINAL DISPERSION AT STEADY AND UNSTEADY FLOWS, COLORADO RIVER, GLEN CANYON DAM TO LAKE MEAD

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ABSTRACT

The effect of channel geometry and unsteadiness of flow on traveltime and longitudinal dispersion of flow in the Colorado River in Glen and Grand Canyons was evaluated in 1989 and 1991 by injecting a fluorescent dye and sampling for dye concentration at selected sites downstream. Measurements of a 26-kilometer reach of Glen Canyon, just below Glen Canyon Dam, were made at nearly steady discharges of 139, 425, and 651 cubic meters per second. A 380-kilometer reach of Grand Canyon was measured at a steady flow of 425 cubic meters per second and an unsteady flow with a daily mean discharge of about 425 cubic meters per second. In Glen Canyon, flow velocity through the study reach increased directly with discharge, but dispersion was much greater at the lowest of the three flows measured than at the higher two flows. Increased dispersion at low flow is thought to be caused by the emergence of cobble bars. In Grand Canyon, flow velocity varied slightly from reach to reach at both steady and unsteady flow but was not significantly different at steady and unsteady flow over the entire study reach. Also, longitudinal dispersion was not significantly different during steady and unsteady flow. The rate of longitudinal dispersion, as measured by rate of decrease in peak concentration and of increase in dye-cloud variance and duration at a site, agrees with that predicted by one-dimensional theory much more closely than is commonly found in rivers. Long tails on the time-concentration curves at a site, characteristic of most rivers but not predicted by the one-dimensional theory, were not found in this study. Absence of tails shows that, at the measured flow, the eddies that are characteristic of the study reach do not trap water for a significant length of time.

INTRODUCTION

Measurements of traveltime and longitudinal dispersion of flow in the Colorado River below Glen Canyon Dam (fig. 1) were made in October 1989 and May 1991 to evaluate the effects of channel geometry and unsteadiness of flow on these fundamental flow characteristics. The measurements are a key part of a program of data collection to support the development of physically based flow and transport models of the river. Data collection and model development are a part of an interagency, interdisciplinary study, the Glen Canyon Environmental Studies (GCES), coordinated by the U.S. Bureau of Reclamation (USBR). Flow and transport models are important to the GCES because assessment of effects of dam operations on all other components of the riparian environment depend on the ability to predict river stage and fluid and sediment transport that result from specified flow releases. Information from this and other GCES research will be incorporated into an Environmental Impact Statement (EIS) on dam operations ordered by the Department of the Interior.

Typically, water is released from Glen Canyon Dam in response to power demand, and resulting releases are very unsteady. As a part of the ongoing environmental studies, Western Area Power Administration (Department of Energy) and the USBR have released water in such a way as to provide opportunities for data collection that would not otherwise be possible. In October 1989, a steady discharge of 142 m^3/s was released for a period of 4 days to provide researchers the opportunity to study low flows. A traveltime and dispersion measurement of the reach from Glen Canyon Dam to Lees Ferry (fig. 1) was made during that steady-release

Figure 1.--Study area and location of dye-sampling sites.

period. Later, researchers and managing agencies agreed to release water to provide a series of "research flows" over a period of about a year, from July 1990 through July 1991. Each research flow occurred over an 11-day period during which the hourly releases had been specified by the researchers. Research flows were designed to provide opportunities to make measurements under known and controlled conditions. Two research flows in May 1991 were selected for the traveltime and dispersion measurements because (1) these flows allowed evaluation of the difference in fluid transport during steady and unsteady releases, which is a prime goal of GCES; (2) these flows were the set of paired steady and unsteady releases with the highest, and approximately equal, daily mean discharge, and high flows have substantially greater capacity for sediment transport than lower flows; (3) a dense network of stage gages was available to provide detailed information on stage changes throughout the reach during the unsteady flow; and (4) suspended-sediment concentrations were expected to be lowest in May, giving less chance of dye loss through adherence to sediment.

Background

Channel geometry of the 406-kilometer study reach is variable and is controlled by bedrock geology to a large degree. Dye sampling sites (fig. 1 and table 1) were selected to define reaches of major differences in geology that control channel slope, width, and depth. Measured reaches range from narrow bedrock channels characterized by rapids and pools typically 15 meters deep or more to wide, shallow channels with large midchannel gravel bars. Geometry of the channel is not well quantified, but some comparison of reaches can be made from sonic depthsounder records of a longitudinal profile and of 200 cross sections made in 1984 (Wilson, 1986). Widths, depths, and areas determined for measured reaches from the 200 cross sections (table 2) were computed by averaging values for cross sections in the specified reach. Cross sections were measured at locations at which it was feasible to manuever a motorized raft across the channel; therefore, locations are biased toward the pool rather than rapid sections. Rapids, however, account for only about 10 percent of the river length. Channel constrictions formed by tributary debris fans, bedrock projections, or talus cause flow separation and eddy zones in all measured reaches. Transfer of water and sediment between the main downstream flow and the eddies is of major concern, because eddies are depositional sites for sand.

A mass of water marked by a tracer dye will move with the mean flow of the stream and mix with surrounding water to form a dye cloud of increasing size and decreasing concentration. In rivers, that mixing and spreading, called dispersion, is caused primarily by turbulent diffusion and velocity gradients (Fischer, 1973). A one-dimensional diffusion equation, in which flux is directly related to a concentration gradient by

Table 1.--Injection and sampling sites for traveltime measurements

Site type	Distance from dam (kilometers)	River mile	Site name
	Glen Canyon reach, 1989		
Injection	0.0	-16.0	Glen Canyon Dam
Sampling	1.5	-15.2	Glen Canyon gage
Sampling	25.9	.0	Lees Ferry gage
	Glen Canyon reach, 1991		
Injection	0.3	-15.9	Below Highway 89 bridge
Sampling	25.9	.0	Lees Ferry gage
	Grand Canyon reach, 1991		
Injection	25.9	0.0	Lees Ferry Gage
Sampling	82.2	35.9	Nautiloid Canyon
Sampling	122.8	61.1	Gage above Little Colorado River
Sampling	147.7	75.8	Below Nevill's Rapid
Sampling	213.8	117.7	Mile 118 Camp
Sampling	292.4	166.5	National Canyon Gage
Sampling	368.1	213.6	Pumpkin Springs
Sampling	405.0	236.0	Gneiss Canyon

Table 2.--Characteristics of reaches defined by dye-sampling sites

[Determined from surveyed cross sections at about 1.6-kilometer intervals at about 680 cubic meters per second. Reach 1, dam to Lees Ferry; 2, Lees Ferry to Nautiloid Canyon; 3, Nautiloid to gage above the Little Colorado River; 4, Little Colorado gage to Nevill's Rapid; 5, Nevill's Rapid to Mile 118 Camp; 6, Mile 118 Camp to National Canyon; 7, National Canyon to Pumpkin Springs; 8, Pumpkin Springs to Gneiss Canyon]

Reach	Length (kilo- meters)	Bed slope	Width (meters)	Depth (meters)	Ratio of width to depth	Area (square meters)
1	24.5	0.00038	99.1	---	----	---
2	57.7	.00141	71.6	8.2	8.7	573
3	40.6	.00126	106.1	6.1	17.4	642
4	24.9	.00274	119.2	5.2	22.9	613
5	66.1	.00195	59.1	8.8	6.7	517
6	78.6	.00151	63.4	7.6	8.3	468
7	75.7	.00134	94.2	6.7	14.1	609
8	36.9	.00161	71.6	9.1	7.9	661

a diffusion coefficient, is commonly used to describe longitudinal dispersion—spreading of a mass of water in a downstream direction—in rivers (Fischer, 1973). According to that theory, the distribution of dye concentration with time at a point downstream from the point at which the dye has become mixed throughout the width and depth of flow will be positively skewed. Variance of the concentration distributions will increase linearly with time, and peak concentration will decrease as the square root of traveltime of the peak concentration (Nordin and Sabol, 1974). A number of studies have shown that the one-dimensional theory does not adequately describe longitudinal dispersion in many rivers (Nordin and Sabol, 1974; Day, 1975; Godfrey and Frederick, 1970; Seo, 1990). Typically, concentration distributions in rivers are more positively skewed, variance of the distribution increases at a greater rate than predicted by the one-dimensional theory. Also, measured distributions have long tails not predicted by the one-dimensional theory. Tails generally are attributed to temporary storage in zones of slowly moving or stagnant water along the channel bed and banks, and much of the effort to develop models of longitudinal dispersion has centered on incorporation of those "dead zones" (Bencala and Walters, 1983; Seo, 1990; Valentine and Wood, 1977).

Purpose and Scope

The purposes of the study were to determine traveltime and longitudinal dispersion characteristics for distinctive subreaches of the study reach at steady flow and to evaluate the effect of unsteady flow on traveltime and dispersion. Data will be used with stage, channel-geometry, and bed-material information to develop a physically based, unsteady-flow model for the study reach. The traveltime measurements will be used to verify the ability of that model to account for transport of the fluid mass. This report presents a preliminary analysis of the data, a discussion of the implication of the results to transport under flow alternatives presented in the Glen Canyon Dam EIS, and a statement of the status of the work.

Acknowledgments

Randy Fabres designed the method of dye injection for the Grand Canyon measurements and piloted the boat during the injection. Tim Deutschlander and Randy Fabres were the boatmen during the Grand Canyon measurements, and their skill and dedication to the goals made it possible to outrun the dye and collect needed samples. Denise Hogan, K.C. Deutschlander, and Monte Becker provided many tasty and nourishing meals under considerable time pressures and difficult conditions. Bernice Cobb and Dan Lunsford volunteered their time to help in the sampling. These measurements could not have been made successfully without the enthusiastic participation of these and the U.S. Geological Survey crew members.

Approach

Measurements were made by injecting rhodamine WT, a red fluorescent dye developed as a water tracer, into the river and collecting water samples during passage of the dye at selected sites downstream from the injection. When possible, sampling began before the arrival of the dye at a site and continued until concentration had reached background values.

The measurement in October 1989 consisted of one injection at Glen Canyon Dam, and sampling at two gaging stations downstream (fig. 1 and table 1). Each May 1991 measurement consisted of two injections—an injection of dye from a point just downstream from the dam and sampling at the Lees Ferry gaging station (the Glen Canyon reach) and a separate injection at the Lees Ferry gage and sampling at locations downstream from Lees Ferry (the Grand Canyon reach) (table 1). In each case, the injection at Lees Ferry was made 2 days before the corresponding injection at the dam. Sample sites were selected to define reaches with significantly different geometry (table 2). The 11 subreaches defined by Schmidt and Graf (1990, table 2, p. 55) were the basis for site selection, but some of the shorter reaches with small differences in geometry were combined into reaches for the traveltime measurements that were feasible to sample.

For the Glen Canyon reach, the traveltime of dye through the reach was expected to be less than a full daily hydrograph, and it was decided to measure the traveltime at the peak discharge of the unsteady flow (651 m^3/s on May 8, 1991). The reach was also measured during the steady 425 m^3/s flow in May 1991. These measurements, together with the measurement made in October 1989 at about 140 m^3/s, give information on traveltime and dispersion at steady flow over much of the powerplant operation range of about 28 to 785 m^3/s. For the Grand Canyon reach, the two May 1991 measurements give information for steady and unsteady flows with about the same daily mean discharge. Discharge at Lees Ferry during the steady-flow measurement, May 20-25, 1991, was 425 m^3/s and during the unsteady-flow measurement, May 6-11, 1991, ranged from 92 to 754 m^3/s with a mean of 428 m^3/s (fig. 2).

Figure 2.--Discharge for the unsteady-flow traveltime measurement at the gaging station, Colorado River at Lees Ferry, Arizona.

METHODS

Established techniques for estimation of dye dosage, sampling, and laboratory analysis of dye samples were used in this study (Wilson and others, 1986; Kilpatrick and Wilson, 1989). Dye dosage was computed using methods presented by Kilpatrick and Wilson (1989, p. 14-15) using an estimated traveltime of the peak concentration. For the Grand Canyon reach, a dosage of 127 kg of dye (635 kg of the 20-percent stock solution) was estimated to give a peak of about 2 μg/L at the end of the reach for the lowest expected velocity; therefore, that amount was injected in the first measurement. Very low dispersion rates kept peak concentrations higher than estimated during that measurement; therefore, half the amount of dye—63.5 kg—was injected for the second measurement. For the Glen Canyon reach, a dosage of 21.5 kg of dye was used for the 1989 measurement and 9.1 kg of dye was used for both 1991 measurements.

Dye was injected over a period of a few minutes in a line across the central part of the cross section. For the 1989 Glen Canyon reach measurement, dye was divided into four equal parts and poured into the river from the transformer deck of the dam at locations on either side of the two generator outlets that were releasing water at the time. The injection took a total of 7 minutes. Samples were collected from the center of flow from cableways at the gaging stations Colorado River below Glen Canyon Dam (09379910) and Colorado River at Lees Ferry (09380000) (fig. 1 and table 1). For the 1991 Glen Canyon reach measurements, dye was poured from a boat as the boat moved across the center part of a cross section of the channel just downstream from the dam. Near-surface dip samples were collected with a hand sampler from three points across the channel from a boat under the cableway at the Lees Ferry gage.

For the Grand Canyon reach, dye was poured from a raft as the raft passed through the center two-thirds of the flow in the cableway section at Lees Ferry. Each injection took about 5 minutes. For sampling, two rafts moved crews from site to site downstream from Lees Ferry. The rafts moved and camped independently, allowing the crews to "leapfrog" downstream, one staying at a sample site to sample the dye cloud, and the other moving ahead to the next site. In addition, two members of the crew of the lead raft were able to camp independently at a third site when it was judged to be advisable to occupy three sites at a time.

Most samples were collected by dipping a sample bottle just under the surface near the stream bank or tossing a bottle in a sample holder into the flow a short distance from the bank. Samples were collected in areas of downstream flow that were judged to be the most evenly distributed across the channel in the vicinity. Most sample sites were at riffles or rapids. Sampling in eddies was avoided. An automatic sampler (Kilpatrick, 1972) was used to collect samples over much of the dye cloud at Pumpkin Springs (table 1).

Discharge at gaging stations was obtained from recorded stage and a stage-discharge relation. An unsteady flow-routing model is being calibrated with data from the gaging stations and stage data from a network of temporary gages. Stage record and rating curves were available for gaging stations (fig. 1) Colorado River below Glen Canyon Dam (09379910); Colorado River at Lees Ferry (09380000); Colorado River above the Little Colorado River, near Desert View (09383100); Colorado River near Grand Canyon (09402500); Colorado River above National Canyon, near

Supai (09404120); and Colorado River above Diamond Creek, near Peach Springs (09404200). The network of temporary stage recorders provided stage information at about 8-kilometer intervals. In addition, stage at sampling sites not near an existing gage was recorded during sampling at the unsteady-flow measurement with a portable gage that consisted of a submersible pressure transducer and datalogger.

Filter fluorometers were used to measure dye concentration in the field to permit adjustment of sampling interval and to ensure that sampling continued until dye was past the site. Samples were collected in glass vials that were capped tightly, packed in opaque boxes, and transferred to the Geological Survey laboratory in Tucson. A set of dye standards was prepared from the dye lot used in the measurements according to the methods described by Wilson and others (1986); the calibration of a Turner[1] Model 10 filter fluorometer was checked with the standards. Measurements of standards and samples were made under constant temperature conditions in the laboratory.

Equivalent background concentration, commonly a result of turbidity, not fluorescence, was determined at most sites by measuring samples of water collected before arrival of the dye cloud. Equivalent background concentration was low—0.01 to 0.14 μg/L. Background concentration was subtracted from concentrations measured in the laboratory to give the concentration values used in this report.

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[1]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

The fraction of injected dye recovered (that is, accounted for by sampling) at each sampling site during steady flow was computed to be above 0.9 (table 3). Errors in the computation include errors incurred because a single sample was used to represent the cross section, in sample analysis, in computation of the area under the time-concentration curves, and in discharge. Discharge values (table 3) were obtained from provisional stage record and rating curves at gaging stations and are likely to be revised when stage record and ratings are reviewed and updated (D.J. Bills, hydrologist, U.S. Geological Survey, oral commun., 1991). These errors account for the fact that the present computation results in more dye recovered at the site below Nevill's Rapid than at the site upstream. Rhodamine WT dye is known to be decomposed by sunlight and to adhere to sediment, and losses in the range of 30-50 percent have been measured in other rivers (Graf, 1986). Recovery ratios have not yet been computed for the unsteady-flow measurement, but initial estimates at two sites suggest that dye loss was greater during unsteady flow. Greater loss may be attributed to stranding of dye in eddy zones when stage dropped. Because recovery ratios are very high and because discharge revisions may be significant, concentrations presented in this preliminary report have not been adjusted to account for dye losses.

Curves of dye concentration as a function of time at a sampling site were plotted, and the first three moments of the distributions were computed using numerical integration. The first moment, dye-cloud centroid, and the rate of travel of the centroid gives velocity through the measured reach. The second and third moments, variance and skewness, are measures of the dispersion, or spreading of the dye cloud.

Table 3.--Recovery ratios for dye at each sampling site for the steady-flow measurement, May 20-25, 1991

[Weight recovered was computed by multiplying the area under the time-concentration curve by the discharge and by a constant factor to correct the units. The correction factor is 0.08640 = 86,400 seconds per day multiplied by 10^{-9} kilograms/microgram multiplied by 1,000 liters per cubic meter. Recovery ratio was computed by dividing the weight recovered by 63.5 kilograms, which is the weight of dye injected]

Site	Area under curve (microgram-days per liter)	Discharge (cubic meters per second)	Weight recovered (kilograms)	Recovery ratio
Nautiloid Canyon	1.6300	425	59.9	0.94
Above the Little Colorado River	1.6358	425	60.1	.95
Below Nevill's Rapid	1.7011	430	63.2	1.00
Mile 118	1.6007	433	59.9	.94
National Canyon	1.5788	436	59.5	.94
Pumpkin Springs	1.5327	436	57.7	.91
Gneiss Canyon	1.5549	436	58.6	.92

RESULTS AND DISCUSSION

Glen Canyon Reach

Results of the Glen Canyon reach measurements show that flow velocity through the reach increases proportionally with discharge, but dispersion is proportionally much greater at the lowest flow than at the higher two flows measured (fig. 3 and table 4). Velocity increased from 0.3 to 1.0 m/s as discharge increased from 139 to 651 m^3/s. The bed slope in the reach is lower than that in downstream reaches (table 2), and velocity at 425 m^3/s is less than that of any of the downstream reaches at that discharge. Peak dye concentration was normalized by dividing by the weight of dye injected and multiplying by the discharge, giving a quantity called unit peak concentration (Kilpatrick and Taylor, 1986; Hubbard and others, 1982). Dye loss was insignificant during each measurement, and no adjustment of concentration for loss was required.

The changes in unit peak concentration, dye-cloud variance, and dye-cloud skewness with discharge all show that dispersion is much greater at the lowest flow than at the two highest flows (fig. 3). Duration of the dye cloud past Lees Ferry, measured from the time of arrival of the dye to the time when a concentration of 10 percent of the peak concentration was reached on the trailing edge of the dye cloud, is also proportionally much greater at the lowest flow than the two highest flows. Duration was 4.5 hours at 651 m^3/s, 6.5 hours at 425 m^3/s, and 12.3 hours at 139 m^3/s. Quantitative measures of changes in spatial characteristics of flow are not available, but qualitative observation suggests that the increased dispersion at low flow results from a change in channel geometry and sinuosity caused by the emergence of large cobble bars and riffles.

Figure 3.--Relation of reach velocity, dye-cloud skewness, dye-cloud variance, and unit-peak concentration to discharge, Glen Canyon reach.

Table 4.--Statistics of the time-concentration curves, Glen Canyon, 1989 and 1991

Distance from injection (kilometers)	Discharge (cubic meters per second)	Maximum concentration (micrograms per liter)	Time (hours) Centroid	Time (hours) Peak	Time variance (hours squared)	Coefficient of skew	Reach velocity (meters per second)
			Measurement, 1989				
1.5	144	61.2	1.35	1.12	0.115	1.238	----
25.9	139	5.78	21.8	20.2	10.4	1.225	0.33
			Steady-flow measurement, 1991				
25.6	425	2.27	9.84	9.70	1.34	.450	0.72
			Unsteady-flow measurement, 1991				
25.6	651	1.98	7.07	6.60	0.708	.560	1.0

Grand Canyon Reach

Dye was sampled at seven sites in the Grand Canyon reach during the measurement at steady flow (table 1 and fig. 4). The time-concentration curves at these sample sites are unusual in that although the curves have a slight positive skew, they do not have the long tails that are typical of such curves in natural streams. Because of the absence of tails, it was feasible to sample the dye cloud until background concentration had been reached at most sites.

Dye was sampled at six sites during the unsteady-flow measurement, but the leading edge of the dye-cloud was not sampled at several sites (fig. 5). The time-concentration curves for unsteady flow are similar to those for steady flow in that they do not have long tails, but the shapes of curves at individual sites appear to be strongly influenced by discharge changes in the reach as the dye passed. For example, the curve at Nautiloid Canyon for unsteady flow is much like that for steady flow. Discharge was nearly steady at the peak flow of the daily range during most of the time the dye traveled through the reach upstream from that site. However, the curve at the site below Nevill's Rapid has a high negative skewness because discharge was increasing in the reach above that site as the dye passed.

For the steady-flow measurement, velocity varied slightly from reach to reach. The lowest velocity (0.75 m/s) was measured in the reach between Nautiloid Canyon and the Little Colorado River confluence—the Lower Marble Canyon reach of Schmidt and Graf (1990, table 2, p. 55). The

Figure 4.--Variation of dye concentration with time at sampling sites, steady-flow traveltime measurement, May 20-25, 1991.

Figure 5.--Variation in dye concentration with time at sampling sites, unsteady-flow traveltime measurement, May 6-11, 1991.

highest velocity (1.1 m/s) was measured between the Little Colorado River confluence and the site below Nevill's Rapid (Furnace Flats reach) and the two reaches between Mile 118 Camp and Pumpkin Springs (Middle Granite and Muav Gorges). Velocity was not significantly correlated with any of the channel geometry characteristics given in table 2.

Velocity of flow in individual reaches during unsteady flow ranged from 0.67 m/s in the Lower Marble Canyon reach to 1.3 m/s in the reach between the site below Nevill's Rapid and the site at Mile 118 Camp (Granite Gorge). For unsteady flow, differences in velocity through individual reaches were more strongly influenced by discharge in the reach as the dye passed than by the geometry of the reach.

Traveltime of the dye-cloud centroid increased linearly with distance traveled for both steady and unsteady flow. Although velocity varied from reach to reach during both measurements, velocity differences were not great enough to significantly alter the traveltime-distance relation (fig. 6). Traveltime was slightly less during unsteady flow than during steady flow, but velocity over the entire measured reach was not significantly different—0.98 m/s for steady flow and 1.0 m/s for unsteady flow.

Downstream changes in peak concentration and dye-cloud variance and duration time are all measures of the longitudinal dispersion. For steady flow, peak concentration decreased as the square root of traveltime (fig. 7). Peak concentration was 12.5 μg/L at the first sampling site, 57.7 km downstream from the injection, and was 5.3 μg/L at the last site, 380 km from the injection. Nonlinear regression

Figure 6.--Relation of traveltime of the dye-cloud centroid to distance traveled, Grand Canyon reach.

Figure 7.--Relation of peak concentration to distance traveled, Grand Canyon reach.

Table 5.--Statistics of the time-concentration curves for the steady-flow measurement, Grand Canyon, May 20-25, 1991

[Reach velocity was computed as velocity of the centroid of the time-concentration curve]

Distance from injection (kilometers)	Discharge (cubic meters per second)	Peak concentration (micrograms per liter)	Time (hours)		Time variance (hours squared)	Coefficient of skew	Reach velocity (meters per second)
			Centroid	Peak			
57.7	425	12.5	18.5	18.4	1.48	1.161	0.87
98.3	425	8.34	33.5	33.1	4.16	.543	.75
123.2	430	8.33	39.9	39.3	4.49	.505	1.1
189.3	433	6.91	58.8	58.6	5.25	.290	.97
267.9	436	6.03	79.0	79.0	6.23	.251	1.1
343.6	436	5.34	98.4	98.3	8.10	.368	1.1
380.5	436	5.32	108.3	107.9	9.36	.253	1.0

Table 6.--Statistics of the time-concentration curves for the unsteady-flow measurement, Grand Canyon, May 6-11, 1991

[Discharge is the mean at the site for the period of passage of the dye cloud. Reach velocity was computed as velocity of the peak concentration]

Distance from injection (kilometers)	Discharge (cubic meters per second)	Peak concentration (micrograms per liter	Time (hours)		Time variance (hours squared)	Coefficient of skew	Reach velocity (meters per second)
			Centroid	Peak			
57.7	362	18.1	14.3	13.8	1.60	0.805	1.1
98.3	336	13.4	31.2	32.3	9.31	-.111	.67
123.2	([1])	10.9	38.0	39.0	6.35	-.526	1.0
189.3	([1])	9.97	--	53.0	--	--	1.3
267.9	([1])	9.74	--	76.5	--	--	.93
380.5	([1])	8.11	103.6	101.7	14.3	.658	1.2

[1]NA, not yet available.

techniques were used to fit an equation of the form $C_p = aT_p^b$, where C_p is peak concentration and T_p is traveltime of the peak concentration, to the data. An exponent of -0.50 was obtained. This is a slower rate of decrease in peak concentration than is typical, but it is about the rate that would be expected if the one-dimensional mixing theory holds. Peak concentrations were higher during the unsteady-flow measurement because of the greater amount of dye injected, but rate of decrease was about the same as that for steady flow.

For steady flow, dye-cloud variance increased with distance traveled and with traveltime (fig. 8). The exponent of a equation of the form given above relating variance to traveltime of the peak concentration is 0.80, lower than any of the measured values presented in a summary of dispersion data by Nordin and Sabol (1974), and lower than that predicted by the one-dimensional theory. Variance increased with distance and traveltime during unsteady flow, but the increase was less systematic (fig. 8). Duration of the dye cloud, measured from the time of first arrival of the dye at the site to the time at which concentration returned to background, was 15.5 hours for steady flow and 17.5 hours for unsteady flow at the site 380 km downstream from the injection. For steady flow, duration increased with traveltime of the peak concentration according to the relation $T_d = 2.4\ T_p^{0.45}$, where T_d is dye-cloud duration in hours. The increase in dye-cloud duration is slower than is typical (Graf, 1986; Kilpatrick and others, 1989).

For the steady-flow measurement, time-concentration curves at all sites were positively skewed (fig. 9). Skewness decreased with time and distance, and curves approach a normal distribution toward the

Figure 8.--Relation of dye-cloud variance to traveltime of the dye-cloud centroid, Grand Canyon reach

Figure 9.--Relation of dye-cloud skewness to traveltime of the dye-cloud centroid, Grand Canyon reach.

downstream end of the study reach. Skewness for sites during the unsteady-flow measurement is positive or negative, depending on the way in which discharge changed during dye passage. Curves for sites in which the discharge increased in the reach upstream as the dye passed are negatively skewed, whereas those for which the discharge was steady or decreasing are positively skewed. None of the curves for the Grand Canyon reach have the long tails typical of most streams.

Implications for Flow Alternatives

Results suggest that unsteadiness of flow has little effect on flow velocity or dispersion at the relatively high mean discharge at which the Grand Canyon reach was measured in this study. Initial estimates of dye losses during steady and unsteady flow indicate that some water may be temporarily stranded by decreasing stage during unsteady flow. In the Glen Canyon reach, flow velocity varies directly with mean discharge, but dispersion is much greater at the lowest of the three measured flows than at the two highest flows. Greater dispersion apparently is caused by the emergence of large cobble bars at low flow (140 m^3/s). Because similar changes in channel geometry occur in some individual reaches of the Grand Canyon study reach, the low dispersion measured in the Grand Canyon reach at steady and unsteady flow may not be indicative of dispersion during flow releases with a low mean discharge.

A one-dimensional unsteady-flow routing model developed by Jobson (1989) was calibrated with stage and discharge data from two research flow periods, February 1-7, 1991, and May 6-12, 1991. The model uses the diffusion wave form of the momentum equation, which neglects acceleration terms. The model has been found to give good results for streams with relatively high slopes in which severe backwater conditions and flow reversals do not occur. (Jobson, 1989). Discharge data from the five streamflow-gaging stations at Lees Ferry and downstream (fig.1) and stage data from temporary stage recorders at river miles 35.9, 76.5, 115.0, 190.1, 214.8, and 248.5 were used to calibrate the model.

The calibrated model provides discharge estimates for use in a solute transport model. Discharges computed for dye sample sites for the unsteady-flow measurement will be used to compute dye losses for that measurement.

Dye-transport data from the steady-flow measurement were used to calibrate a one-dimensional solute-transport model developed by Jobson and Schoellhamer (1987). The model, which solves the one-dimensional convection-dispersion equation in a LaGrangian reference frame, has been found to estimate realistic values of longitudinal dispersion coefficients for a wide range of situations (Jobson, 1987). Model results fit the observed data very well—mean error (computed-observed concentration) ranged from -0.0062 to 0.073 μg/L for reaches downstream from Nautiloid Canyon. Root mean squared error was 0.12-0.14 μg/L for those reaches. The reach from Lees Ferry to Nautiloid Canyon includes the inital mixing length, in which mixing takes place in three dimensions, and mean and root mean squared errors were larger for that reach—0.13 and 0.27 μg/L, respectively.

Longitudinal dispersion coefficents were computed from the measured time-concentration curves by the method of moments (Yotsukura and other, 1970) and from model results (table 7). According to Jobson (1987), dispersion coefficients computed from model results represent the physical processes better than do coefficients computed by the method of moments. The longitudinal dispersion coefficient is computed from model results using the relation $D_f = D/(u^2 dt)$, where D_f is the dimensionless dispersion factor (a model-calibration parameter), D is the longitudinal dispersion coefficient in length squared per time, u is mean flow velocity, and dt is the model time step. Jobson (1987) showed that the accuracy of the dispersion coefficient computed from model results depends on the value of D_f and therefore on the model time step. For D_f greater than about 0.1, the error in computed dispersion coefficient is less than 3 percent, but the error increases sharply for D_f less than about 0.1 (Jobson, 1987, figure 2). For the 0.25-hour time step used for model calibration, D_f less than 0.1 were computed for reaches 4 and 6 (table 7), and the model dispersion coefficients for those reaches may have significant errors.

Time-concentration curves at dye sample sites in the Grand Canyon reach were estimated with the calibrated model for three steady and two unsteady releases, 226 m^3/s (8,000 ft^3/s), 425 m^3/s (15,000 ft^3/s), 850 m^3/s (30,000 ft^3/s), and EIS flow alternatives 4 and 6 (fig. 10). For the EIS alternatives, discharge was simulated at 0.25-hour increments for a 7-day period in July using a computer program that fits a sine function within the seasonal minimum and maximum discharges specified by the EIS team for that alternative (J.P. Bennett, research hydrologist, U.S. Geological Survey, written commun., 1992). The daily mean discharge of each of the two flow alternatives was 425 m^3/s; therefore, model results provide a comparison of steady releases, releases with low fluctuations, and releases with high fluctuations for the same daily mean discharge.

Model results predict that velocity increases directly with discharge for steady releases (fig. 11). The Lees Ferry reach measurements showed that although velocity increased with discharge,

Table 7.--Reach velocity and longitudinal dispersion coefficients at steady releases of 425 cubic meters per second.

[Reach 2, Lees Ferry to Nautiloid Canyon; 3, Nautiloid to gage above the Little Colorado River; 4, Little Colorado gage to Nevill's Rapid; 5, Nevill's Rapid to Mile 118 Camp; 6, Mile 118 Camp to National Canyon; 7, National Canyon to Pumpkin Springs; 8, Pumpkin Springs to Gneiss Canyon]

Reach	Length (kilo-meters)	Velocity (meters per second)		Dispersion factor (Df)	Longitudinal dispersion coefficient (square meters per second)	
		Peak	Centroid		Model	Method of moments
2	57.7	0.91	0.87	0.20	164	109
3	40.6	0.79	0.75	0.30	213	181
4	24.9	1.02	1.08	0.06	55.1	108
5	66.1	0.98	0.97	0.18	159	68.1
6	78.6	1.08	1.08	0.09	87.5	102
7	75.7	1.08	1.08	0.20	194	202
8	36.9	1.00	1.03	0.15	139	243

Figure 10.--Discharges simulated to represent Environmental Impact Studies flow alternatives 4 and 6 for July 1-7.

Figure 11.--Relation of velocity of peak solute concentration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.

dispersion was much greater at the lowest measured flow than at the highest two flows measured. For the Grand Canyon reach, the model predicts that unit peak concentration is lower at the lowest discharge than a linear relation would yield (fig. 12), but that predicted solute-cloud duration, a measure of dispersion, decreases approximately linearly with discharge (fig. 13). The difference between the observations in the Lees Ferry reach and the model predictions for the Grand Canyon reach may be caused by the inability of the model, calibrated at 425 m^3/s, to account for changes in the effective geometry at low flow.

For unsteady flows, the model predicts that velocity in individual reaches will be higher or lower than for steady flows, depending on the timing of the passage of the trough and peak of the discharge wave. Averaged over the entire reach, the model predicts that velocity is about the same for steady and unsteady releases, as was found from the measurements for unsteady and steady releases. The difference between steady and unsteady releases is less for unit peak concentration and solute-cloud duration than it is for reach velocity.

Ongoing work includes running the model at a smaller time step to increase the accuracy of computed dispersion coefficients, verification of the model for the unsteady-release measurement, computation of dye recovery for the unsteady-release measurement, use of model result to plan a low-flow measurement for the Grand Canyon reach, and comparison of results for the Colorado River measurements to those for other streams.

Figure 12.--Relation of unit peak solute concentration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.

Figure 13.--Relation of solute-cloud duration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.

CONCLUSIONS

The preliminary analysis of traveltime and dispersion data presented above support the following conclusions:

1. The relation of peak concentration, dye-cloud variance, and dye-cloud duration to traveltime of the dye-cloud peak show that dispersion in the study reach is less than is commonly found in other rivers.
2. The data fit a simple one-dimensional mixing model, without modifications to account for dead zones better than do data for many rivers for which measurements are available.
3. The absence of tails on the time-concentration curves shows that retention time of water in eddies is very short; the eddies do not act as dead zones.
4. Differences from reach to reach in large-scale channel geometry and slope have a relatively small effect on flow velocity and dispersion.
5. Unsteadiness of flow affects the velocity through individual reaches, but velocity over the entire 380-kilometer Grand Canyon reach is not significantly different at steady and unsteady flow. Unsteadiness of flow does not appear to affect the rate of dispersion significantly.
6. Channel-geometry changes at low flow significantly increase the dispersion in the Glen Canyon reach and probably also increase the dispersion in at least some of the individual reaches in the Grand Canyon reach.
7. One-dimensional unsteady-flow and solute-transport models calibrated with data from research flow periods provide a good fit with observed data and can be used to make predictions about solute transport.

These conclusions will continue to be examined during the ongoing analysis.

REFERENCES CITED

Bencala, K.E. and Walters, R.A., 1983, Simulation of solute transport in a mountain pool-and-riffle stream—A transient storage model: American Geophysical Union, Water Resources Research, v. 19, no. 3, p. 718-724.

Day, T.J., 1975, Longitudinal dispersion in natural channels: American Geophysical Union, Water Resources Research, v. 11, no. 6, p. 909-918.

Fischer, H.B., 1973, Longitudinal dispersion and turbulent mixing in open-channel flow: Annual Review of Fluid Mechanics, v. 5, p. 59-78.

Godfrey, R.G., and Frederick, B.J., 1970, Stream dispersion at selected sites: U.S. Geological Survey Professional Paper 433-K, 38 p.

Graf, J.B., 1986, Traveltime and longitudinal dispersion in Illinois streams: U.S. Geological Survey Water-Supply Paper 2269, 65 p.

Hetling, L.J., and O'Connell, R.L., 1966, A study of tidal dispersion in the Potomac River: American Geophysical Union, Water Resources Research, v. 2, no. 4, p. 825-841.

Hubbard, E.F., Kilpatrick, F.A., Martens, L.A., and Wilson, J.F., Jr., 1982, Measurement of time of travel and dispersion in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A9, 44 p. [in part superseded by Kilpatrick and Wilson, 1989]

Jobson, H.E., 1987, Estimation of dispersion and first-order rate coefficients by numerical routing: American Geophysical Union, Water Resources Research, v. 23, no. 1, p. 169-180.

__________1989, Users manual for an open-channel streamflow model based on the diffusion analogy: U.S. Geological Survey Water-Resources Investigations Report 89-4133, 73 p.

Jobson, H.E. and Schoellhamer, D.H., 1987, Users manual for a branched Lagrangian transport model: U.S. Geological Survey Water-Resources Investigations Report 87-4163, 73 p.

Kilpatrick, F.A., 1972, Automatic sampler for dye tracer studies: American Geophysical Union, Water Resources Research, v. 8, no. 3, p. 737-742.

Kilpatrick, F.A., and Taylor, K.R., 1986, Generalization and applications of tracer dispersion data: American Water Resources Association, Water Resources Bulletin, v. 22, no. 4, p. 537-548.

Kilpatrick, F.A., and Wilson, J.F., Jr., 1989, Measurement of time of travel in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A9, 27 p.

Kilpatrick, F.A., Rathbun, R.E., Yotsukura, Nobuhiro, Parker, G.W., and DeLong, L.L., 1989, Determination of stream reaeration coefficients by use of tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A18, 52 p.

Nordin, C.F., Jr., and Sabol, G.V., 1974, Empirical data on longitudinal dispersion in rivers: U.S. Geological Survey Water-Resources Investigations Report 20-74, 332 p.

Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.

Scott, C.H., Norman, V.W., and Fields, F.K., 1969, Reduction of fluorescence of two tracer dyes by contact with a fine sediment, *in* Geological Survey Research 1969: U.S. Geological Survey Professional Paper 650-B, p. B164-B168.

Seo, I.W., 1990, Laboratory and numerical investigation of longitudinal dispersion in open channels: American Water Resources Association, Water Resources Bulletin, v. 26, no. 5, p. 811-822.

Valentine, E.M., and Wood, I.R., 1977, Longitudinal dispersion with dead zones: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 103, p. 975-990.

Wilson, J.F., Jr., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing [revised]: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A12, 31 p.

Wilson, R.P., 1986, Sonar patterns of Colorado riverbed, Grand Canyon: Fourth Federal Interagency Sedimentation Conference, v. 2, Las Vegas, Nevada, March 24-27, 1986, Proceedings, p. 5-133 to 5-142.

Yotsukura, Nobuhiro, Fischer, H.B., and Sayre, W.W., 1970, Measurement of mixing charateristics of the Missouri River between Sioux City, Iowa, and Plattsmouth, Nebraska: U.S. Geological Survey Water-Supply Paper 1899-G, 29 p.

ILLUSTRATIONS

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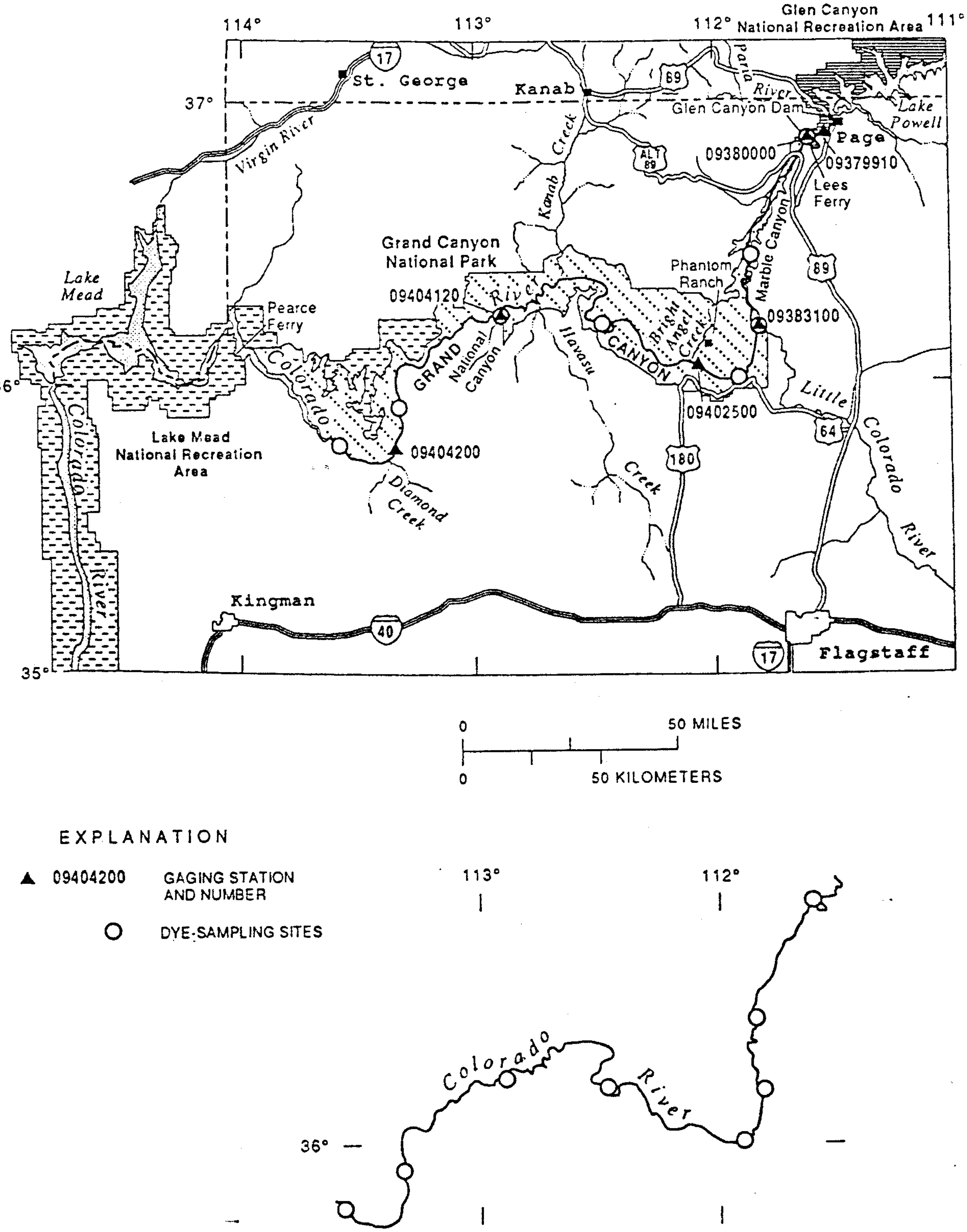

Figure 1.-Study area and location of dye-sampling sites.

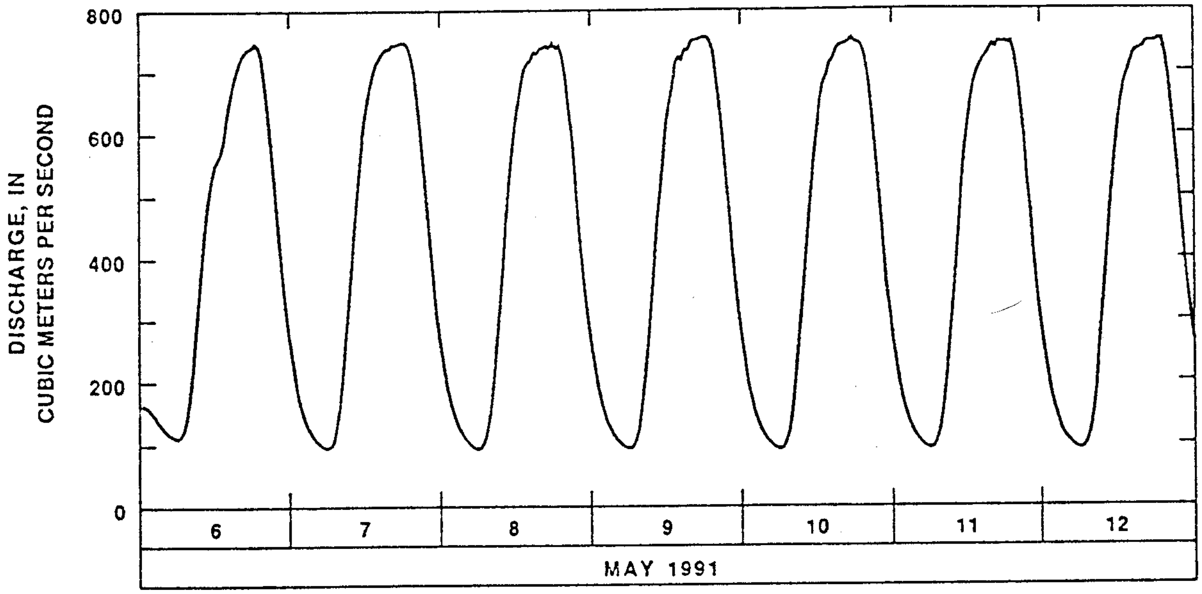

Figure 2.–Discharge for the unsteady-flow traveltime measurement at the gaging station, Colorado River at Lees Ferry, Arizona.

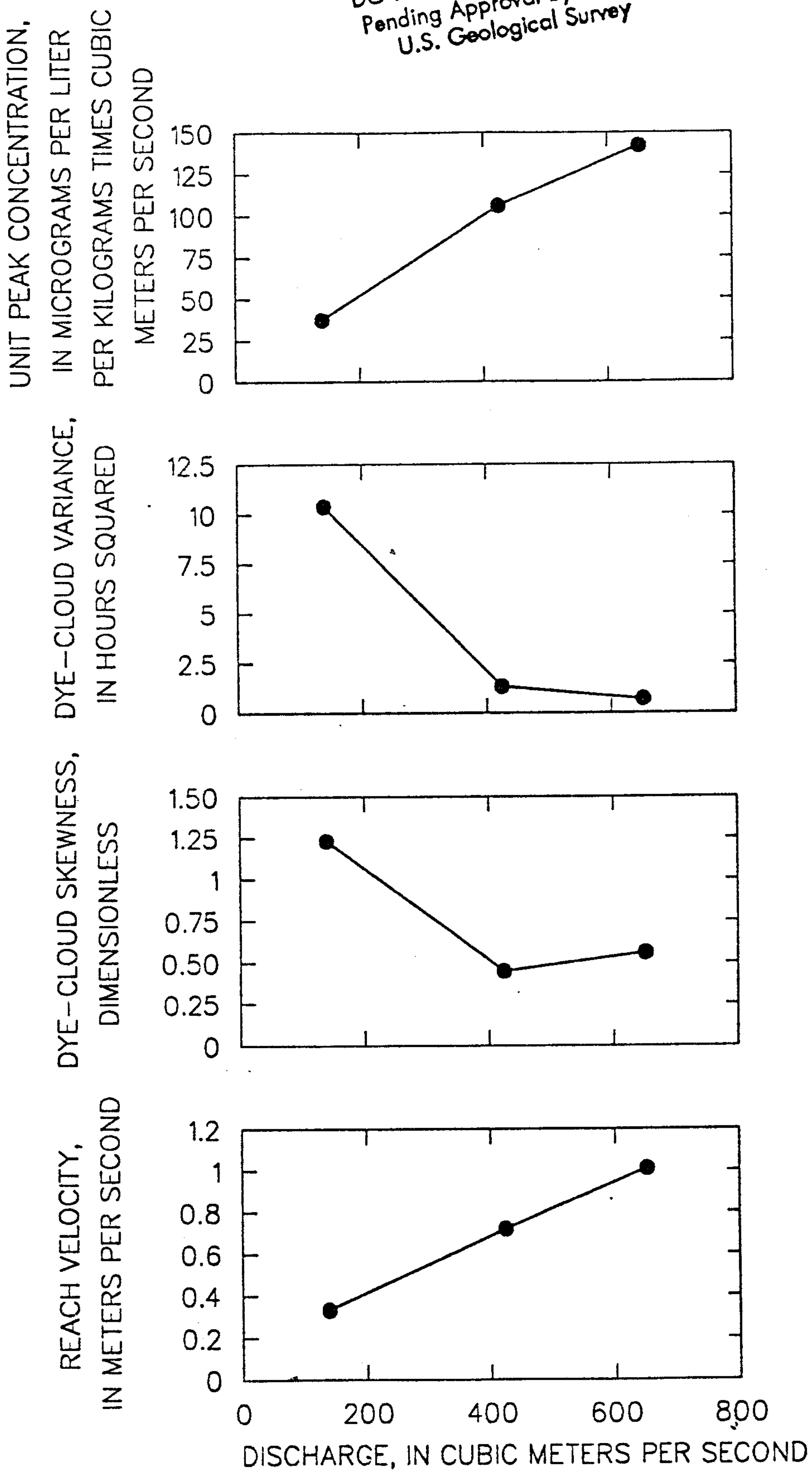

Figure 3.--Relation of reach velocity, dye-cloud skewness, dye-cloud variance, and unit-peak concentration to discharge, Glen Canyon reach.

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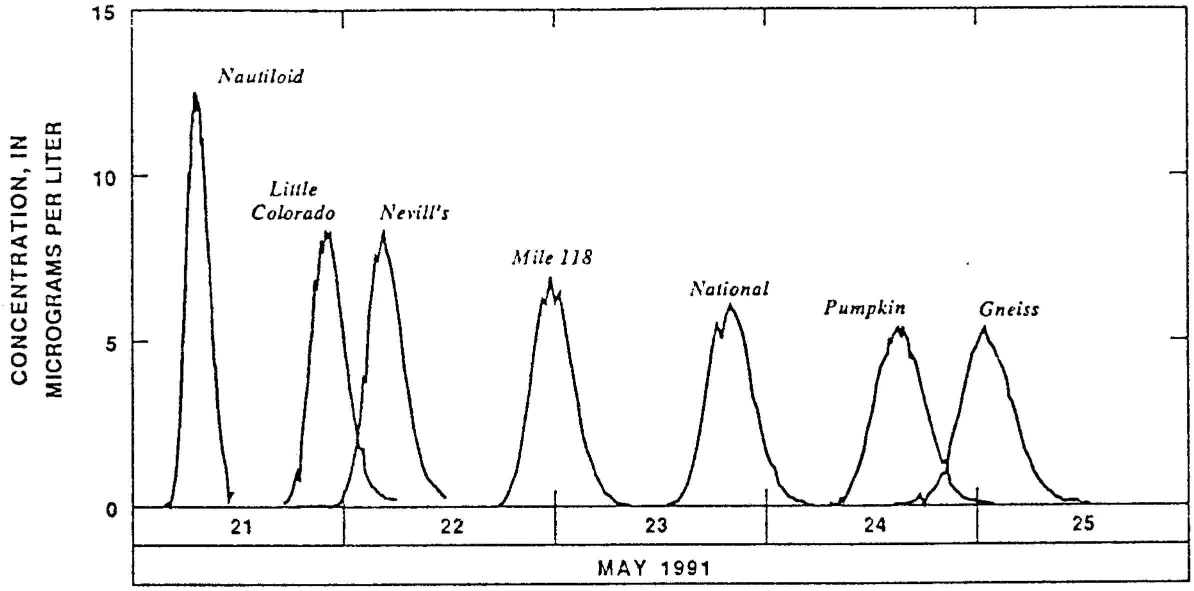

Figure 4.—Variation of dye concentration with time at sampling sites, steady-flow traveltime measurement, May 20-25, 1991.

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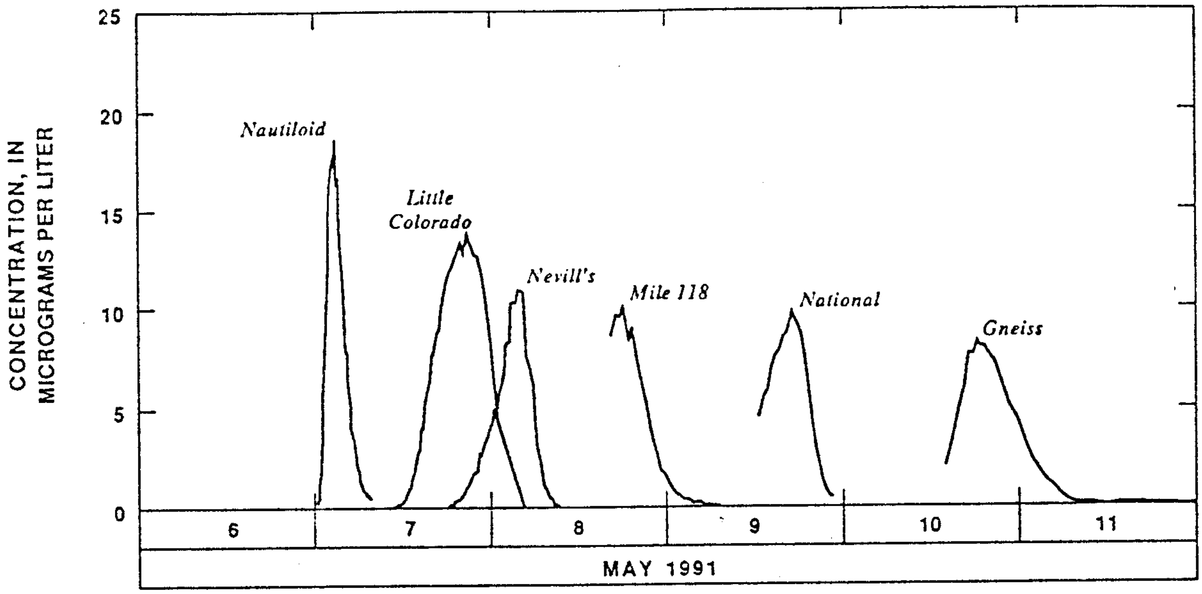

Figure 5.—Variation in dye concentration with time at sampling sites, unsteady-flow traveltime measurement, May 6-11, 1991.

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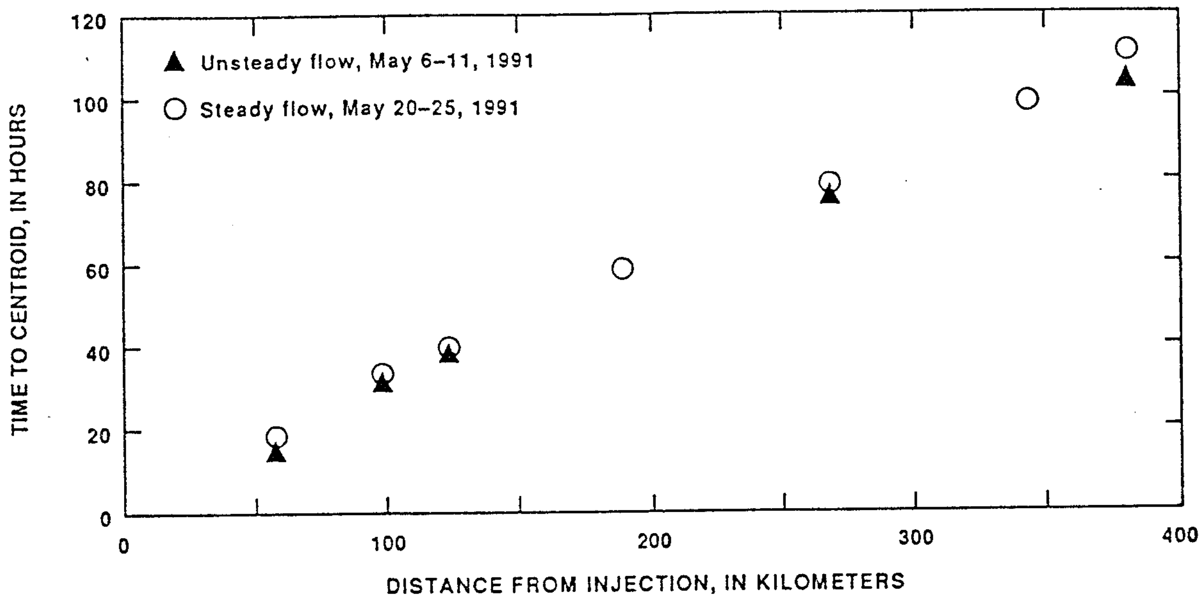

Figure 6.--Relation of traveltime of the dye-cloud centroid to distance traveled, Grand Canyon reach.

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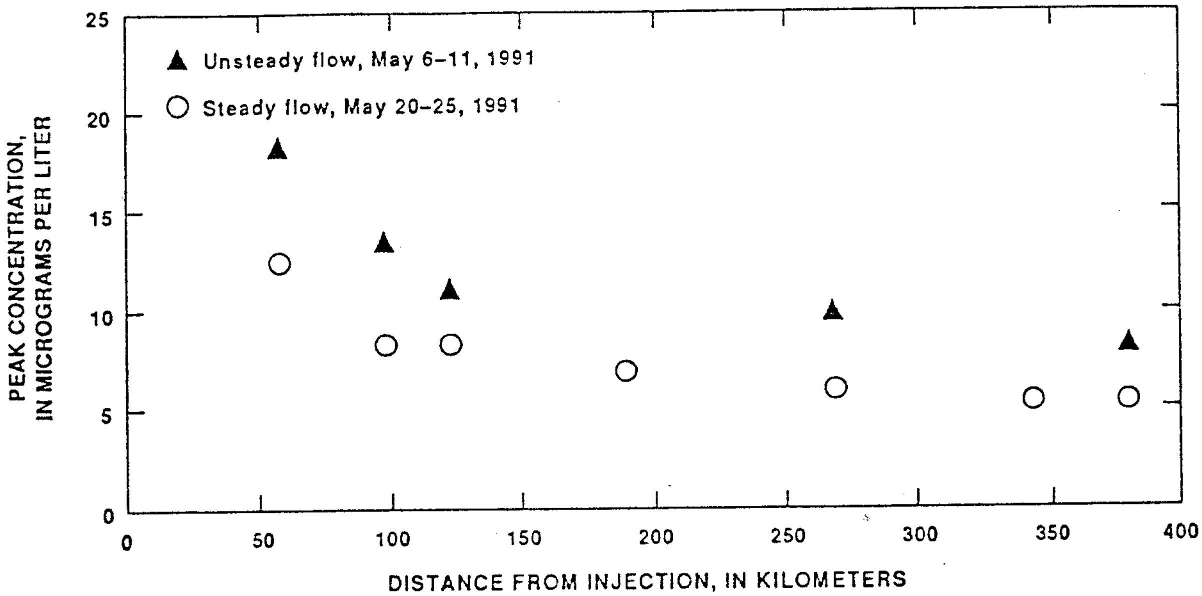

Figure 7.–Relation of peak concentration to distance traveled, Grand Canyon reach.

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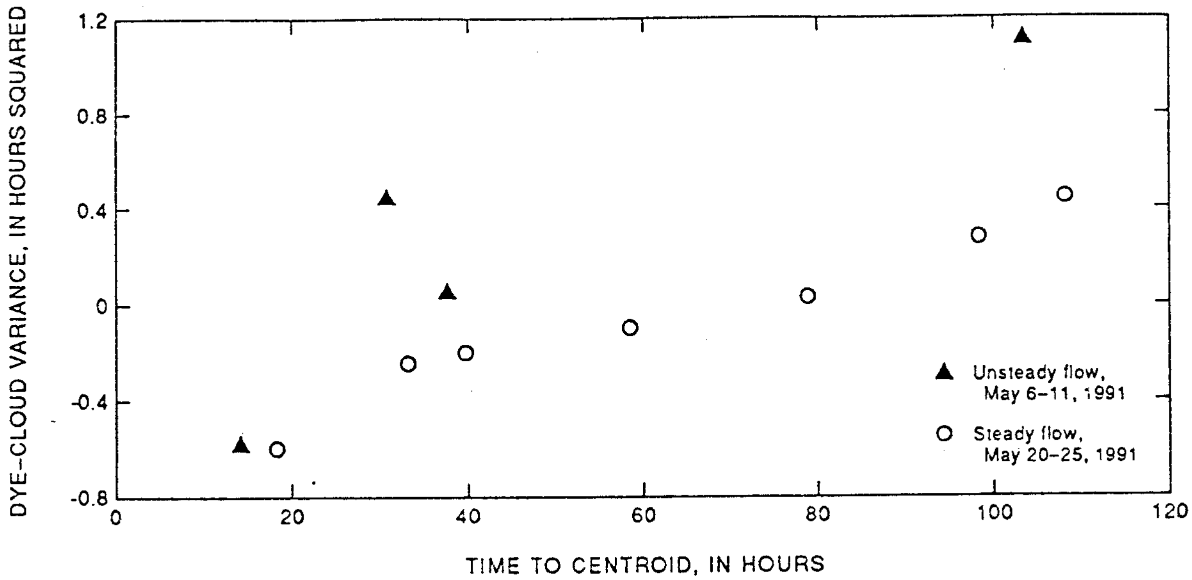

Figure 8.—Relation of dye-cloud variance to traveltime of the dye-cloud centroid, Grand Canyon reach.

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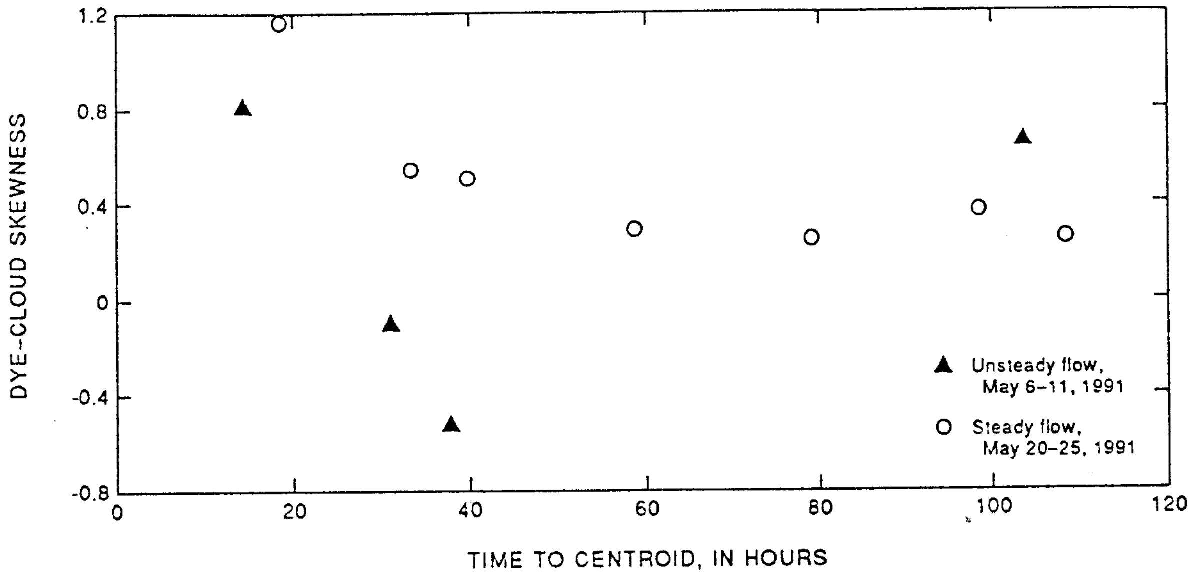

Figure 9.—Relation of dye-cloud skewness to traveltime of the dye-cloud centroid, Grand Canyon reach.

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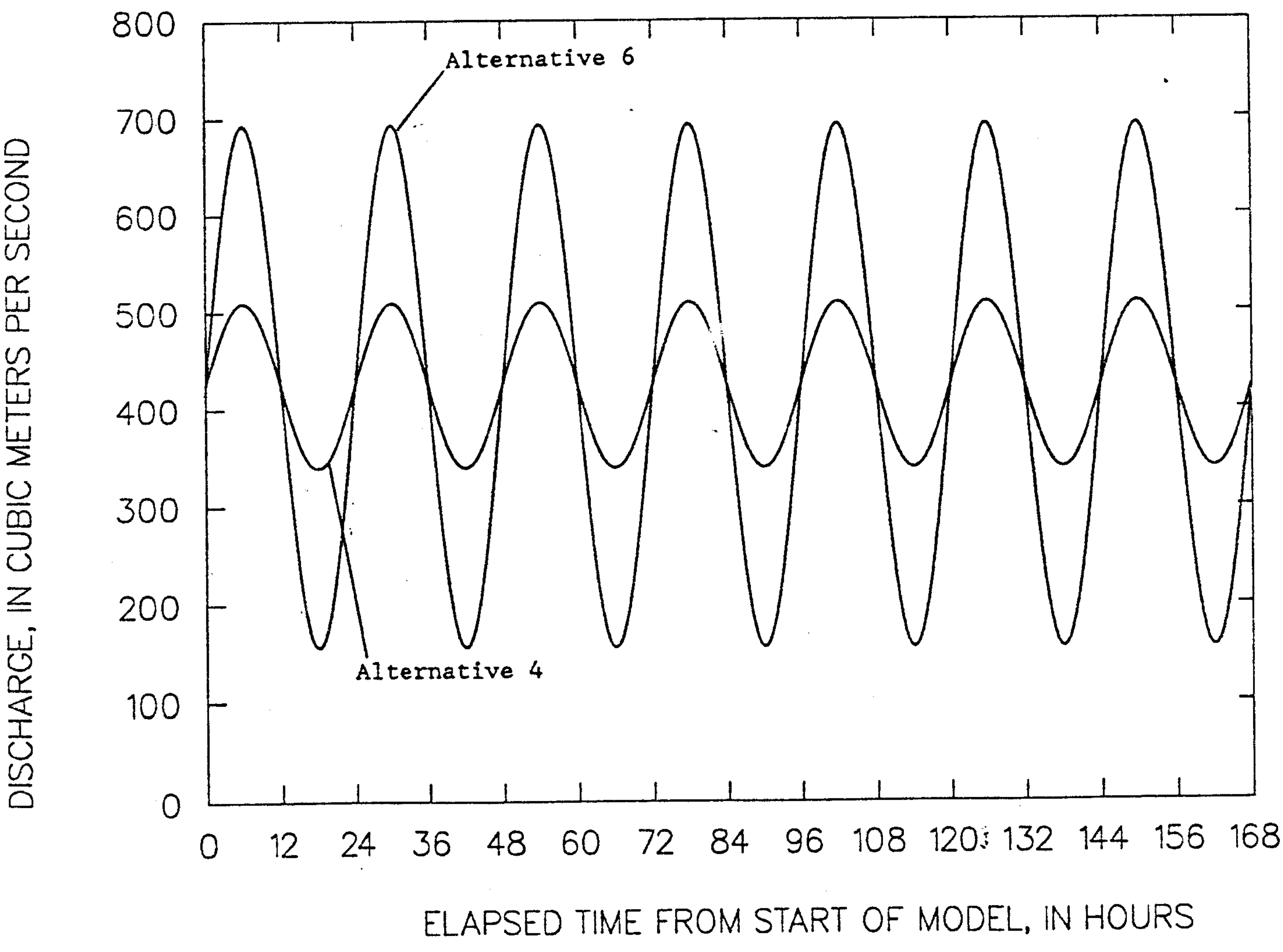

Figure 10.--Discharges simulated to represent Environmental Impact Studies flow alternatives 4 and 6 for July 1-7.

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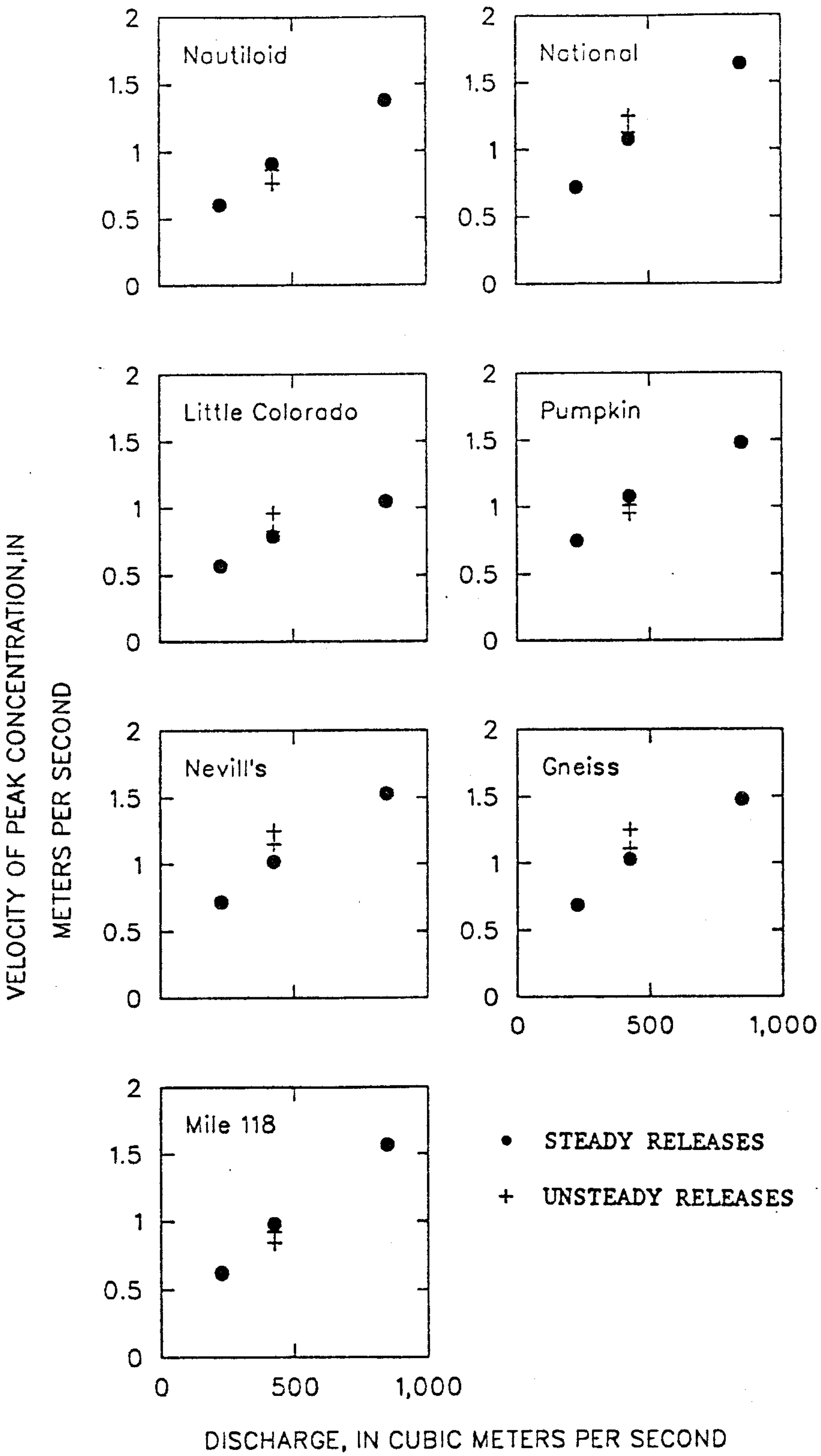

Figure 11.--Relation of velocity of peak solute concentration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.

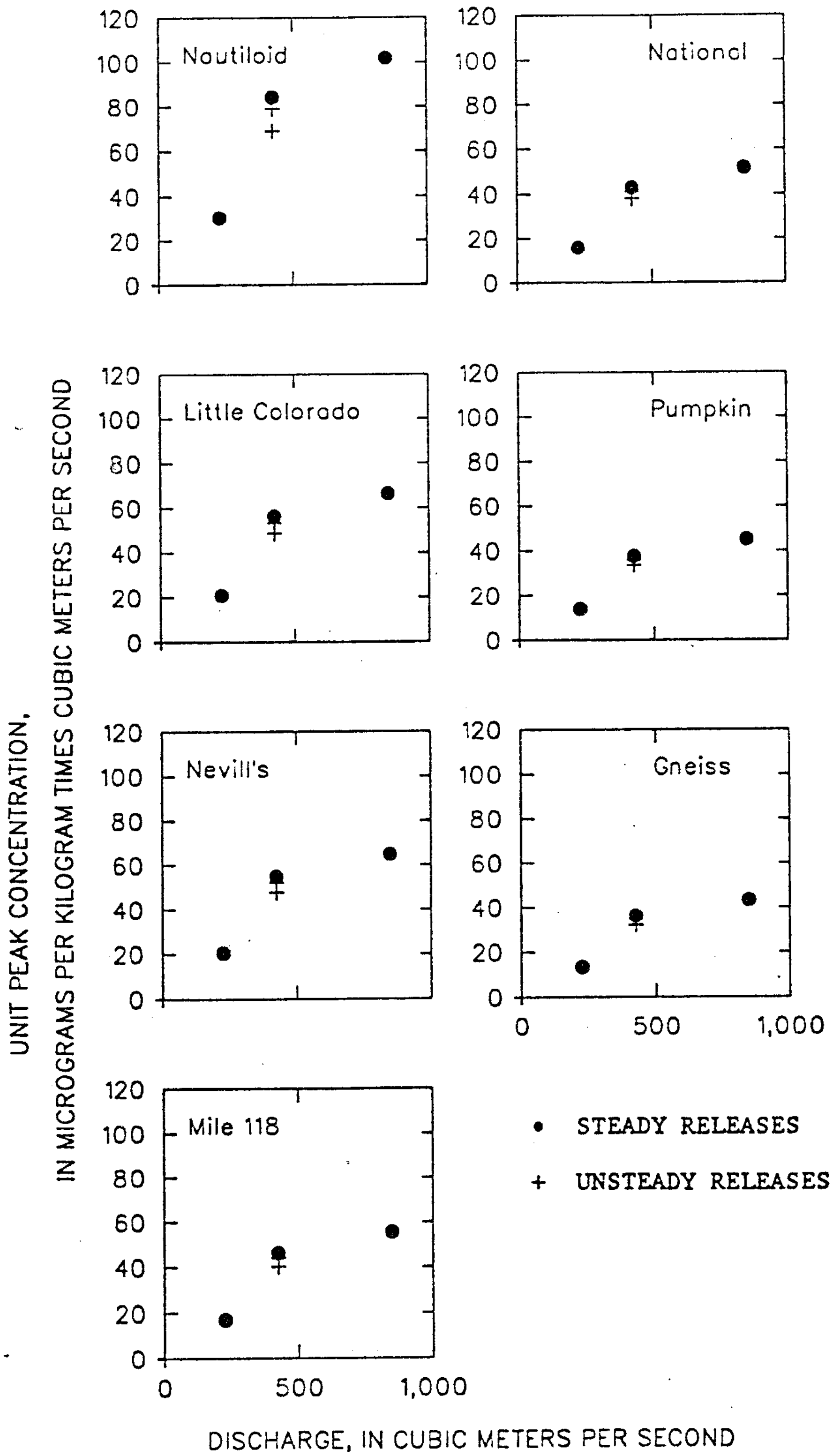

Figure 12.--Relation of unit peak solute concentration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.

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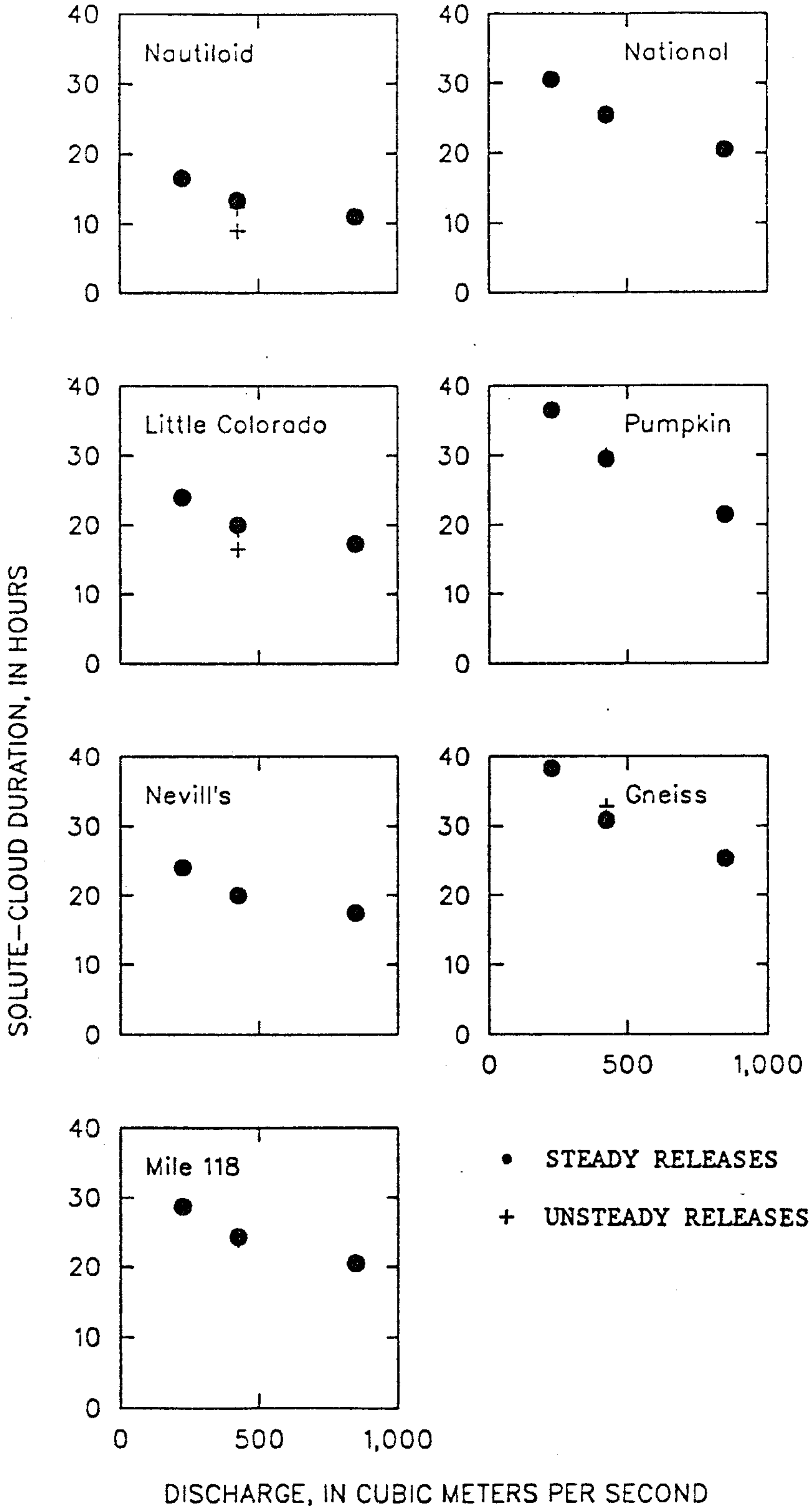

Figure 13.--Relation of solute-cloud duration estimated by a solute-transport model to discharge for three steady and two unsteady dam releases.