VOL. 31, NO. 2 WATER RESOURCES BULLETIN AMERICAN WATER RESOURCES ASSOCIATION APRIL 1995

MEASURED AND PREDICTED VELOCITY AND LONGITUDINAL DISPERSION AT STEADY AND UNSTEADY FLOW, COLORADO RIVER, GLEN CANYON DAM TO LAKE MEAD[1]

Julia Badal Graf[2]

ABSTRACT: The effect of unsteadiness of dam releases on velocity and longitudinal dispersion of flow was evaluated by injecting a fluorescent dye into the Colorado River below Glen Canyon Dam 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 dam releases of 139, 425, and 651 cubic meters per second. Measurements of a 380-kilometer reach of Grand Canyon were made at steady releases of 425 cubic meters per second and at unsteady releases with a daily mean of about 425 cubic meters per second. In Glen Canyon, average flow velocity through the study reach increased directly with discharge, but dispersion was greatest at the lowest of the three flows measured. In Grand Canyon, average flow velocity varied slightly from subreach to subreach 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. 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 on the curves shows that, at the measured flows, the eddies that are characteristic of the Grand Canyon reach do not trap water for a significant length of time. Data from the measurements were used to calibrate a one-dimensional flow model and a solute-transport model. The combined set of calibrated flow and solute-transport models was then used to predict velocity and dispersion at potential dam-release patterns.

(KEY TERMS: flow velocity; longitudinal dispersion; steady flow; unsteady flow; tracers; water policy/regulation/decision making; Glen Canyon Dam; Colorado River.)

INTRODUCTION

Measurements of velocity and longitudinal dispersion of flow in the Colorado River below Glen Canyon Dam (Figure 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 by the U.S. Geological Survey (USGS). Measured velocity is used to estimate bed roughness for flow-routing models developed as part of the overall program (Flow and Sediment Transport in the Colorado River Between Lake Powell and Lake Mead, J. D. Smith and S. M. Wiele, written communication, 1992; A Discharge Model of the Colorado River Through the Grand Canyon, S. M. Wiele and J. D. Smith, written communication, 1993).

USGS data collection and model development are a part of an interagency, interdisciplinary study, the Glen Canyon Environmental Studies (GCES), coordinated by the Bureau of Reclamation (BOR). The goal of the study is to provide managers of the dam and downstream resources the means to predict the effects of different dam-release patterns on the riparian system downstream from the dam. 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 dam releases. Information from this and other GCES research has been incorporated into an Environmental Impact Statement (EIS) on dam operations ordered by the Department of the Interior and submitted to the Secretary of the Interior in March 1995. To aid in the evaluation of potential dam-release patterns that is a part of the EIS, velocity, and dispersion data were used to calibrate existing flow and solute-transport models and the calibrated models used to predict velocity and dispersion for two of the dam-release patterns under evaluation.

[1]Paper No. 93145 of the *Water Resources Bulletin*. **Discussions are open until December 1, 1995.**

[2]Research Hydrologist, U.S. Geological Survey, 375 South Euclid Avenue, Tucson, Arizona 85719.

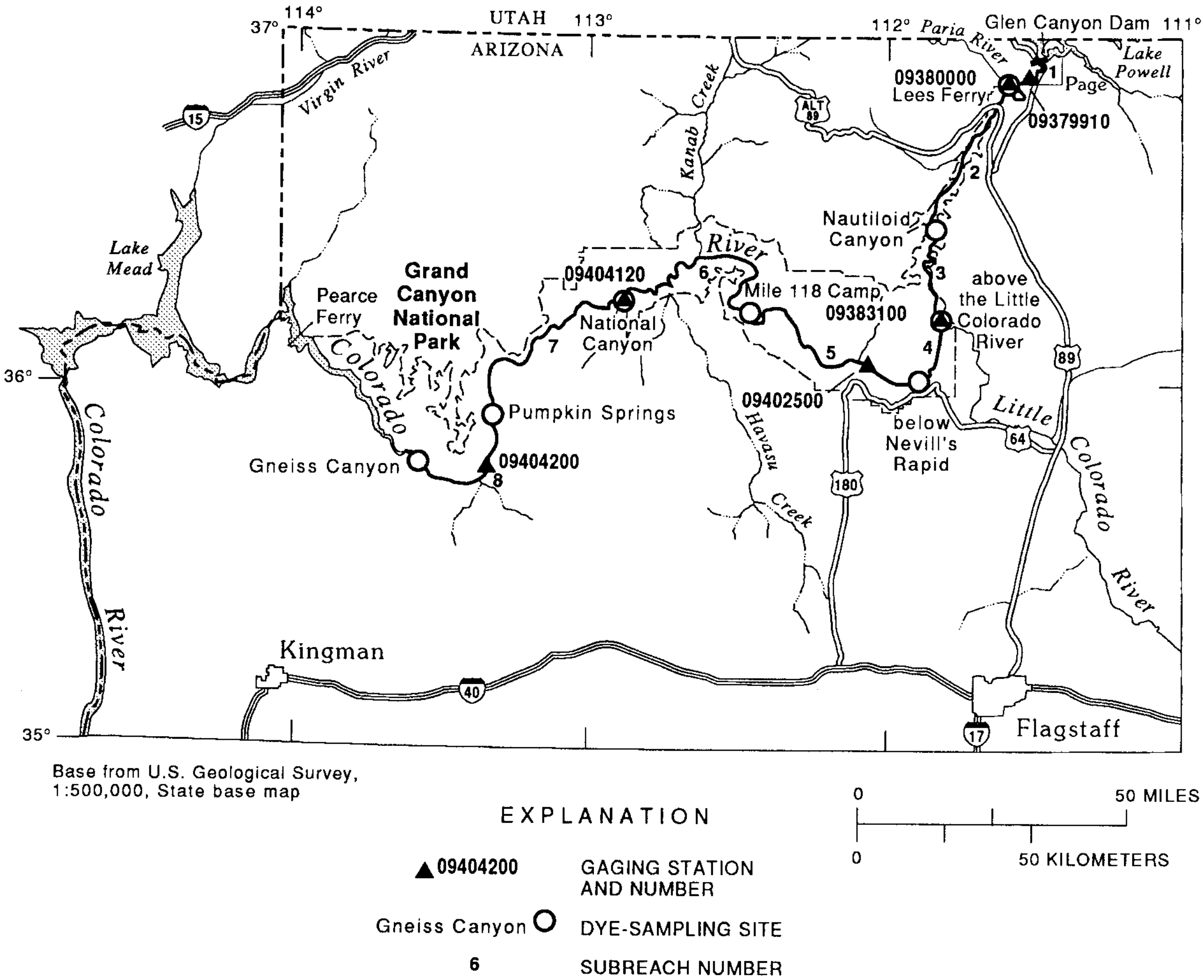

Figure 1. Study Area and Location of Dye-Sampling Sites and Subreaches.

Releases from Glen Canyon Dam can range from about 30 to about 850 m^3/s. Daily mean releases have been higher than the powerplant capacity of about 850 m^3/s only about 3 percent of the time since 1963 (U.S. Department of the Interior, 1994). Typically, water is released from the dam in response to power demand, and resulting releases are high in the middle of the day and low at night. The time-varying dam releases produce discharges that vary rapidly with time – are unsteady – in the reach downstream from the dam (Figure 2). Median daily range in releases has been between 340 and 450 m^3/s since flow regulation began in 1963. Rate of change of releases was between about 110 and 230 m^3/s per hour about 60 percent of the time from 1966-1989 (U.S. Department of the Interior, 1994). The National Park Service, U.S. Fish and Wildlife Service, and Arizona Game and Fish Department, which manage resources downstream from the dam, and the public have become concerned that unsteady dam releases are adversely affecting the riparian environment. The concerns and potential adverse effects have been summarized in a final report of the first phase of the GCES (U.S. Department of the Interior, 1989) and in a review report by a committee of the Water Science and Technology Board of the National Research Council (National Research Council, 1987).

As a part of the ongoing environmental studies, the Western Area Power Administration (U.S. Department of Energy) and the BOR have released water in such a way as to provide opportunities for data collection that otherwise would not be possible. In October 1989, a steady discharge of 142 m^3/s was released for a period of four days to provide researchers the opportunity to study low flows. Reach-average velocity and longitudinal dispersion in the reach from Glen Canyon Dam to Lees Ferry (Figure 1) were measured during that steady-release period. Later, researchers and managing agencies agreed to release water to provide a series of "research flows" from July 1990

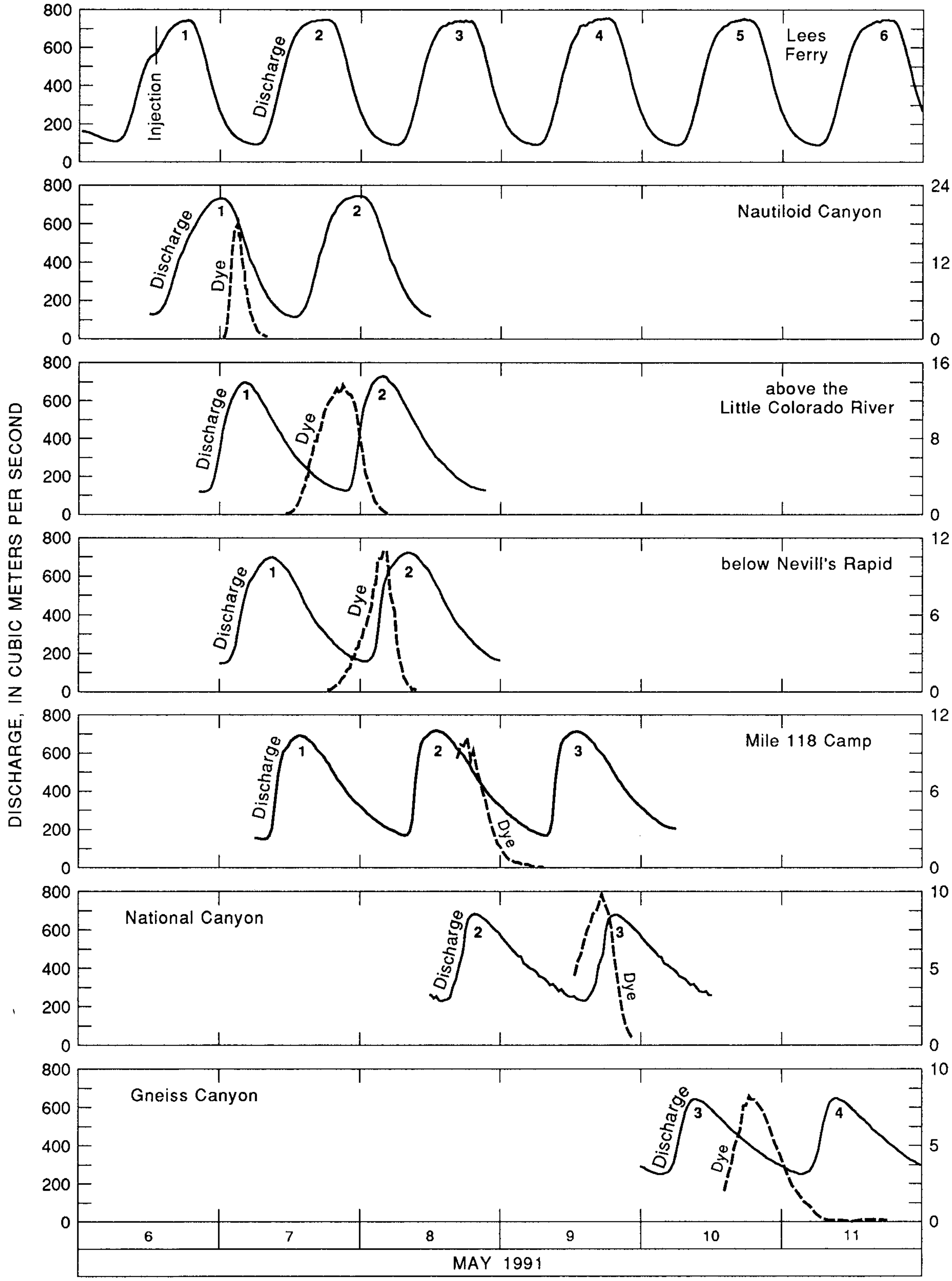

Figure 2. Discharge at the Streamflow-Gaging Station, Colorado River at Lees Ferry, Arizona, and Discharge and Dye Concentration at Sampling Sites in the Grand Canyon Reach for the Unsteady-Flow Traveltime Measurement.

through July 1991. Each research flow took place over an 11-day period during which the hourly releases had been specified by the researchers. Research flows were planned to provide opportunities to make measurements under known and controlled steady and unsteady flow conditions. The unsteady research flows were designed to test releases similar to those for power generation – low releases at night and high releases during the middle of the day. Two research flows in May 1991 were selected for velocity and dispersion measurement because (1) these flows allowed evaluation of the difference in fluid transport during steady and unsteady releases; (2) these flows were the pair of steady and unsteady releases with the highest, and approximately equal, daily mean discharge (425 m^3/s), 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 study reach during the period of unsteady flow; and (4) suspended-sediment concentrations, and therefore loss of dye through adherence to sediment, were expected to be lowest in May. High suspended-sediment concentrations typically result from runoff in tributaries, and in northeast Arizona, rainstorms that produce runoff are less likely in the late spring and early summer than at other times of the year.

Description of the Study Reach

Channel geometry of the 406-kilometer study reach is variable and to a large degree controlled by bedrock type and structure (Howard and Dolan, 1981). More than 60 percent of the bed is covered by bedrock, talus blocks, and boulders (Wilson, 1986). Geometry ranges from narrow bedrock channels characterized by rapids and pools typically 15 m or more deep to wide, shallow, channels with large midchannel gravel bars. Sand is stored in the pools in thin, discontinuous layers on a bedrock or gravel bed. Channel constrictions formed by debris deposits at the mouths of tributary streams, bedrock projections, or talus cause flow separation and eddies in all measured reaches. Although eddies occur in most streams, they are a characteristic feature of the Colorado River in Grand Canyon where the very rough and resistant bed causes flow separation in many locations (Schmidt and Graf, 1990; Schmidt, 1990). Typical eddies range in length from 150 to 500 m at moderate flow, and flow velocity in eddies is typically 20 to 40 percent of the velocity in the downstream flow of the adjacent main channel (Schmidt, 1990). Transfer of water and sediment between the main downstream flow and the eddies is of major concern because eddies are the primary depositional sites for sand bars in this incised bedrock river. Also, shallow areas with low-velocity flow are formed in the eddy zones when stage in the main channel is low enough to expose the sand bars that are typical of the eddy zones. The low-velocity areas, called backwaters by fisheries biologists, may be important to the survival of native fish (Maddox *et al.,* 1987).

Study Approach

Measurements were made by injecting rhodamine WT, a red fluorescent dye developed as a water tracer, into the river and collecting water samples as the dye passed selected sites downstream from the injection. Sampling was planned to begin before the arrival of the dye at a site and continue until the dye had passed the sample site.

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 length and decreasing concentration. Mixing and spreading in rivers are 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 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 – the mean concentration or centroid of the dye cloud will trail the peak concentration. Variance of the concentration distribution will increase linearly with time, and peak concentration will decrease as the square root of traveltime of the peak concentration increases (Nordin and Sabol, 1974). A number of studies have shown that 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 and variance of the distribution increases at a greater rate than predicted by one-dimensional theory. Also, measured distributions typically have long tails not predicted by one-dimensional theory. The tails generally are attributed to temporary storage in zones of slowly moving or nonconveying parts of the channel along the channel bed and banks. Much of the effort to develop models of longitudinal dispersion has focused on accounting for the "dead zones" along the channel (Bencala and Walters, 1983; Seo, 1990; Valentine and Wood, 1977).

In the present study, dye-sampling sites were selected to define subreaches of major differences in geology that control channel slope, width, and depth (Figure 1). The 11 subreaches defined by Schmidt and Graf (1990, Table 2, p. 55) were the basis for site selection, but some of the shorter subreaches with small differences in geometry were combined into subreaches that were long enough to make sampling possible with the constraints of available personnel and boat travel time on the river. Geometry of the channel in measured subreaches was defined from sonic depth-sounder records of a longitudinal profile and 199 cross sections measured in 1984 (Wilson, 1986). Widths, depths, and areas determined for measured subreaches from the cross sections (Table 1) were computed by averaging values for cross sections in the specified subreach. In the study by Wilson (1986), cross sections were measured at locations where it was feasible to maneuver a motorized raft across the channel; therefore, cross sections were not surveyed at sections where rapids occurred. Rapids, however, account for only about 10 percent of the river length.

Data on velocity and dispersion during flows at and above the range of powerplant releases that are potential management options are required. For the Glen Canyon reach, two measurements made in May 1991 and one in October 1989 provide information on velocity and dispersion at steady flow over much of the powerplant operating range of about 30 to 850 m^3/s. Velocity was measured at the peak discharge of the unsteady flow (651 m^3/s on May 8, 1991) because the dye was expected to travel through the reach during the passage of only a small part of the daily hydrograph. Measurements also were made in the reach during the steady flow of 425 m^3/s in May 1991 and in October 1989 at 139 m^3/s. The 1991 measurements on the Grand Canyon reach were scheduled to evaluate the effect of unsteady flow on velocity and dispersion for a mid-range release from the powerplant. Discharge at Lees Ferry during the steady-flow measurement, May 20-25, 1991, was 425 m^3/s; during the unsteady-flow measurement, May 6-11, 1991, discharge ranged from 92 to 754 m^3/s with a daily mean discharge of 428 m^3/s (Figure 2). The study plan includes two measurements that have not yet been made – the Grand Canyon reach at a steady discharge of about 140 m^3/s and both reaches at about 1300 m^3/s. The highest discharge is about equal to the sum of the maximum releases possible through the powerplant and releases through the river outlet works.

Data from the velocity and dispersion measurements were used to calibrate a one-dimensional flow model, DAFLOW, and a solute-transport model, BLTM, developed by Jobson (1989) and Jobson and Schoellhamer (1987), respectively. The calibrated models were then used to predict velocity and dispersion for two of the dam-release patterns under evaluation as a part of the Glen Canyon Dam EIS.

MEASURED VELOCITY AND DISPERSION

Methods

Tracer Dosage and Injection. The measurement in October 1989 consisted of one injection at Glen Canyon Dam and sampling at two gaging stations downstream (Figure 1). Each 1991 measurement consisted of two injections – an injection of dye from a point just downstream from the dam and sampling at

TABLE 1. Characteristics of Subreaches Defined by Dye-Sampling Sites.

[Determined from surveyed cross sections at about 1.6-kilometer intervals at a discharge of about 680 cubic meters per second. Subreach 1 – Glen Canyon 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. Subreach 1 is the Glen Canyon reach and subreaches 2-8 make up the Grand Canyon reach.]

Subreach	Length (kilometers)	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

the Lees Ferry gaging station (Glen Canyon reach) and a separate injection at the Lees Ferry gage and sampling at locations downstream from Lees Ferry (Grand Canyon reach). In each case, the injection at Lees Ferry was made two days before the corresponding injection at the dam to avoid commingling of the injections.

Established techniques for estimation of dye dosage, sampling, and laboratory analysis of dye samples were used for this study (Wilson *et al.*, 1986; Kilpatrick and Wilson, 1989). 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. For the Grand Canyon reach, a dosage of 127 kg of dye (635 kg of 20 percent stock solution) 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.

Dye was injected as a line source over a period of a few minutes. For the 1989 measurement in the Glen Canyon reach, dye was divided into four equal parts and poured into the river simultaneously from the transformer deck of the dam. For the 1991 measurement in the Glen Canyon reaches, 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. 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.

Tracer Sampling and Sample Analysis. 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 where velocity was judged to be evenly distributed across the channel. An automatic sampler (Kilpatrick, 1972) was used to collect samples over much of the dye cloud at Pumpkin Springs. For measurements in the Glen Canyon reach, samples were collected from the center of flow from cableways at gaging stations Colorado River below Glen Canyon Dam (09379910) and Colorado River at Lees Ferry (09380000) (Figure 1). For the May 1991 measurement, near-surface dip samples were collected from a boat with a hand sampler from three points across the channel. Dye was sampled at seven sites in the Grand Canyon reach during the steady-flow measurement (Figure 1) and at six sites during the unsteady-flow measurement. The leading edge of the dye cloud was not sampled at the three downstream sites during the unsteady-flow measurement.

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 and transferred to the U.S. Geological Survey laboratory in Tucson. Samples were remeasured under constant temperature conditions in the laboratory.

An equivalent background concentration of from 0.01 to 0.14 μg/l, resulting from suspended material rather than dye fluorescence, was established at most sites from measurements of samples collected before arrival of the dye cloud. The background concentration was subtracted from concentrations measured in the laboratory to give the dye concentrations used in the analysis.

Data Analysis. The weight of injected dye recovered at each sampling site during steady flow was computed by multiplying the area under the time-concentration curve by the discharge during sampling and a factor to correct the units. The computation showed that more than 90 percent of dye injected was recovered at sampling sites. Rhodamine WT dye decomposes in sunlight and adheres to sediment. Losses in the range of 30-50 percent have been measured in other rivers (Graf, 1986). Initial estimates at two sites sampled during the unsteady flow measurement indicate 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 of dye was very high, concentrations presented in this 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 is dye-cloud centroid – 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.

A quantity called unit-peak concentration was defined in previous studies (Kilpatrick and Taylor, 1986; Hubbard *et al.*, 1982) to compare results from different measurements. Unit-peak concentration is a peak concentration that has been normalized for discharge, amount of dye injected, and dye loss during measurement. For this study, unit-peak concentration was computed by dividing the measured peak dye concentration by the weight of dye injected and multiplying by the discharge. Dye loss was insignificant during each measurement, and no adjustment of concentration for loss was required.

Discharges at each gaging station were determined from recorded stage and a stage-discharge relation –

rating curve – defined by recent current-meter measurements. Gaging stations with stage record and rating curves were 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) (Figure 1). The network of temporary stage recorders provided stage information at intervals of about 8 kilometers. In addition, stage at sampling sites not near an existing gage was recorded during sampling for the unsteady-flow measurement with a portable gage that consisted of a submersible-pressure transducer and datalogger to provide additional information on the timing of dye passage relative to the passage of the daily hydrograph.

Results

Steady Flow, Glen Canyon Reach. Results show that dispersion was proportionally much greater at the lowest flow than at the highest two flows measured (Figure 3 and Table 2). Velocity increased from 0.3 to 1.0 m/s as discharge increased from 139 to 651 m^3/s. The lower bed slope in the Glen Canyon reach than in downstream subreaches (Table 1) may account for the fact that average velocity at a discharge of 425 m^3/s is less in the Glen Canyon reach than in any of the subreaches of the Grand Canyon reach.

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 (Figure 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, also is proportionally much greater at the lowest flow than the two highest flows. Dye-cloud 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 information from aerial photographs and direct observation indicates that the increased dispersion at low flow results from an increase in sinuosity and in longitudinal velocity gradients caused by the emergence of large cobble bars and riffles.

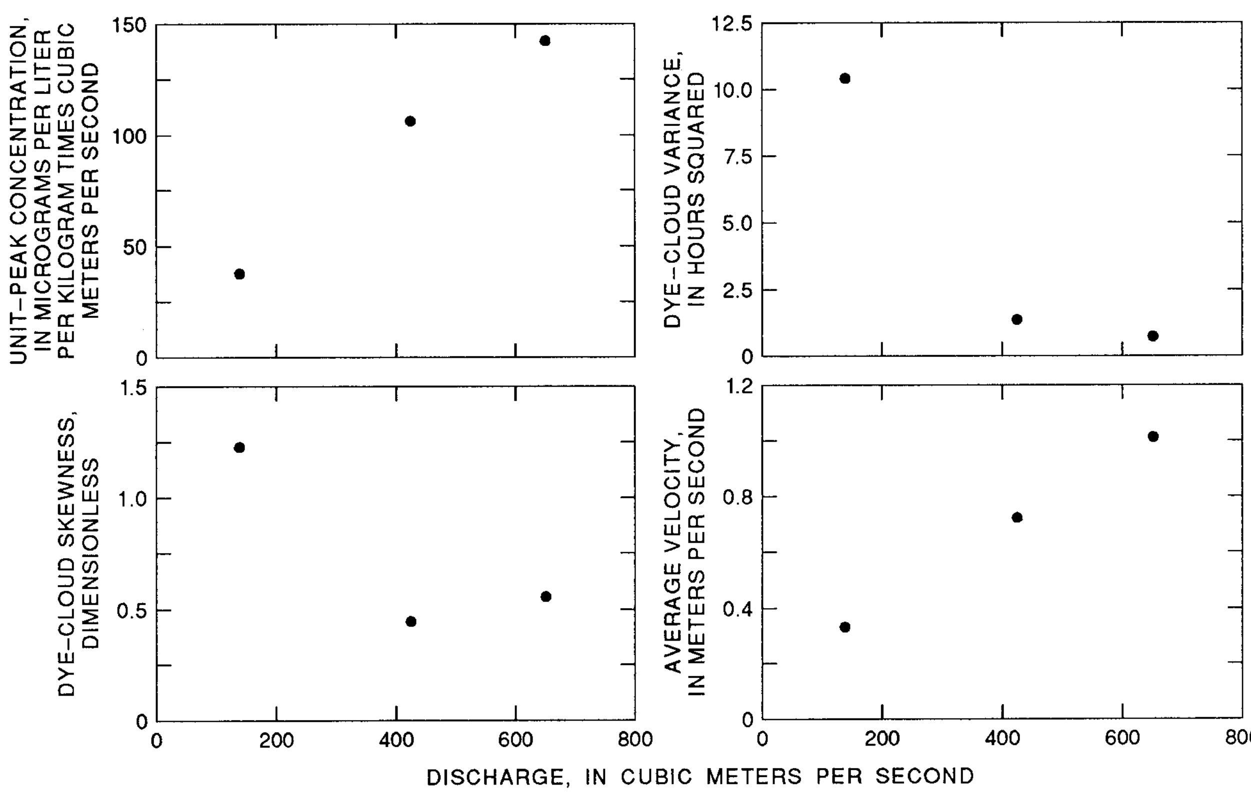

Figure 3. Relation of Average Velocity, Dye-Cloud Skewness, Dye-Cloud Variance, and Unit-Peak Concentration to Discharge, Glen Canyon Reach.

TABLE 2. Statistics of the Time-Concentration Curves, Glen Canyon Reach, 1989 and 1991.
[Average velocity was computed as velocity of the centroid of the time-concentration curve.]

Distance From Injection (kilometers)	Discharge (cubic meters per second)	Maximum Concentration (micrograms per liter)	Time After Injection (hours) Peak	Time After Injection (hours) Centroid	Time Variance (hours squared)	Coefficient of Skew	Average Velocity (meters per second)
			Measurement, 1989				
1.5	144	61.2	1.12	1.35	0.115	1.238	–
25.9	139	5.78	20.2	21.8	10.4	1.225	0.33
			Steady-Flow Measurement, 1991				
25.6	425	2.27	9.70	9.84	1.34	.450	.72
			Unsteady-Flow Measurement, 1991				
25.6	651	1.98	6.60	7.07	0.708	.560	1.0

Steady and Unsteady Flow, Grand Canyon Reach. The time-concentration curves generated from samples collected at steady flow are atypical in that although the curves have a slight positive skew, they do not have the long tails typical of natural streams (Figure 4 and Table 3). 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 are strongly influenced by discharge changes in the reach as the dye passed (Figures 2 and 5). For example, dye curves for sites at which the dye passed during decreasing flow are positively skewed, whereas dye curves for sites where the dye passed on increasing flow are negatively skewed (Figure 2 and Table 3). The dye curve at the site above the Little Colorado River, where the dye passed on the trough of the daily hydrograph, is nearly symmetrical.

For the steady-flow measurement, velocity varied slightly from subreach to subreach (Table 3). The lowest velocity (0.75 m/s) was measured in the subreach between Nautiloid Canyon and the sample site above Little Colorado River – the Lower Marble Canyon reach (Schmidt and Graf, 1990, Table 2, p. 55). The highest velocity (1.1 m/s) was measured between the site above the Little Colorado River and the site below Nevill's Rapid (Furnace Flats reach) and the two subreaches between Mile 118 Camp and Pumpkin Springs (Middle Granite and Muav Gorges). Velocity is not significantly correlated with any of the channel geometry characteristics given in Table 1. Poor correlation of velocity with slope and channel geometry probably is caused by the inadequate characterization of the channel by the 199 measured cross sections.

Velocity of flow in individual subreaches during unsteady flow ranged from 0.61 m/s in the Lower Marble Canyon reach to 1.3 m/s in the subreach between the site below Nevill's Rapid and the site at Mile 118 Camp (Granite Gorge). For unsteady flow, differences in velocity through individual subreaches were more strongly influenced by discharge in the reach as the dye passed than by the geometry of the subreach. Velocity was highest in the subreaches in which the dye cloud traveled near the peak discharge of the daily hydrograph – from Lees Ferry to Nautiloid Canyon, below Nevill's Rapid to Mile 118 Camp, and National Canyon to Gneiss Canyon (Figure 2 and Table 3). The lowest velocity was measured in the reach between Nautiloid Canyon and the Little Colorado River, a reach where the dye cloud traveled with the trough of the daily hydrograph (Figure 2 and Table 3).

Traveltime of the dye-cloud centroid increased linearly with distance traveled for both steady and unsteady flow. Although average velocity varied from subreach to subreach during both measurements, velocity differences were not great enough to significantly affect the linear traveltime-distance relation (Figure 6). Traveltime was slightly less during unsteady flow than during steady flow, but average velocity in 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 are all measures of the longitudinal dispersion. For steady flow, peak concentration decreased as the square root of traveltime. Peak concentration was 12.5 μg/l at the first sampling site, 57.7 km downstream from the injection, and 5.3 μg/l at the last site, 380 km from the injection (Figure 7). Nonlinear regression was used to relate the peak

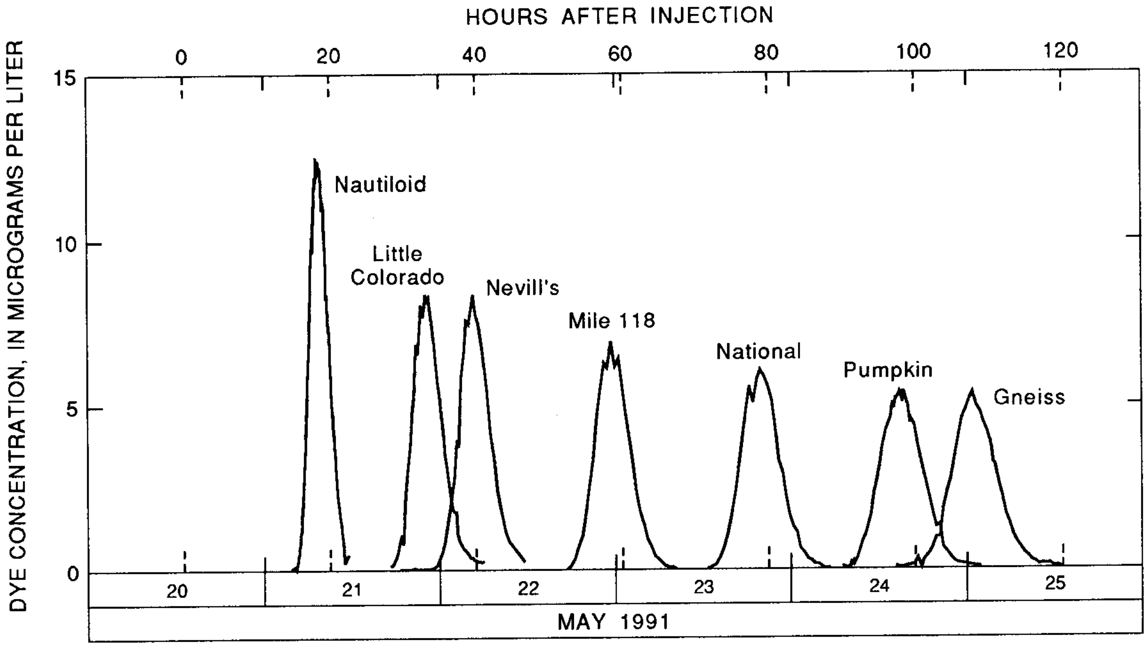

Figure 4. Variation of Dye Concentration with Time at Sampling Sites, Steady-Flow Traveltime Measurement, Grand Canyon Reach, May 20-25, 1991.

TABLE 3. Statistics of the Time-Concentration Curves for the Grand Canyon Reach Measurements, May 1991. [Discharge for the unsteady-flow measurement is the mean at the site for the period of passage of the dye cloud. Average velocity was computed as velocity of the centroid of the time-concentration curve.]

Distance From Injection (kilometers)	Discharge (cubic meters per second)	Maximum Concentration (micrograms per liter)	Time After Injection (hours)		Time Variance (hours squared)	Coefficient of Skew	Average Velocity (meters per second)
			Peak	Centroid			
Unsteady-Flow Measurement, May 6-11, 1991							
57.7	362	18.1	13.8	14.3	1.60	0.805	1.2
98.3	336	13.4	32.3	31.2	9.31	–.111	.61
123.2	(*)	10.9	39.0	38.0	6.35	–.526	1.0
189.3	(*)	9.97	53.0	–	–	–	1.3
267.9	(*)	9.74	76.5	–	–	–	.93
380.5	(*)	8.11	101.7	103.6	14.3	.658	1.2
Steady-Flow Measurement, May 20-25, 1991							
57.7	425	12.5	18.5	18.5	1.48	1.161	0.87
98.3	425	8.34	33.1	33.5	4.16	.543	.75
123.2	430	8.33	39.3	39.9	4.49	.505	1.1
189.3	433	6.91	58.6	58.8	5.25	.290	.97
267.9	436	6.03	79.0	79.0	6.23	.251	1.1
343.6	436	5.34	98.3	98.4	8.10	.368	1.1
380.5	436	5.32	107.5	108.3	9.36	.253	1.0

*NA, not available.

concentration, C_p, to traveltime of the peak concentration, T_p, with an equation of the form $C_p = aT_p{}^b$. The exponent obtained, –0.50, indicates 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 (Nordin and Sabol, 1974). Peak concentrations were higher during the unsteady-flow measurement because of the greater

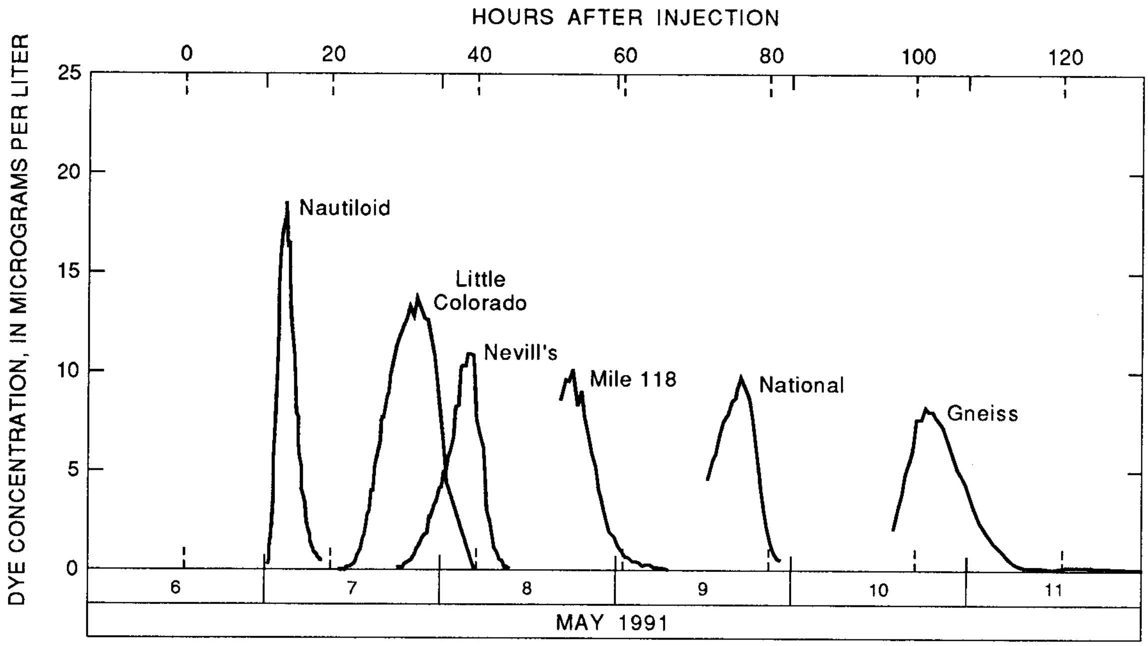

Figure 5. Variation of Dye Concentration with Time at Sampling Sites, Unsteady-Flow Traveltime Measurement, Grand Canyon Reach, May 6-11, 1991.

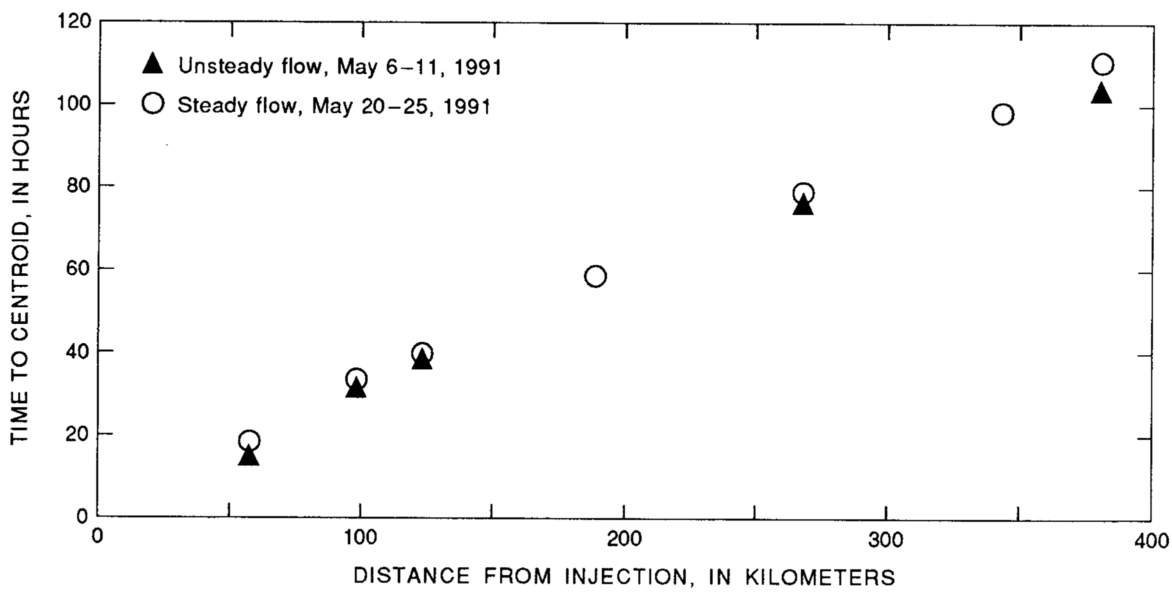

Figure 6. Relation of Traveltime of the Dye-Cloud Centroid to Distance Traveled, Grand Canyon Reach.

amount of dye injected, but the rate of decrease was about the same as that for steady flow – the coefficient in the equation above is different, but the exponent is the same for the two measurements.

For steady flow, dye-cloud variance increased with distance traveled and with traveltime (Table 3 and Figure 8). In order to compare results with those from other streams, an equation of the form given above was fitted to the variance and traveltime of the peak-concentration data. The exponent was found to be 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

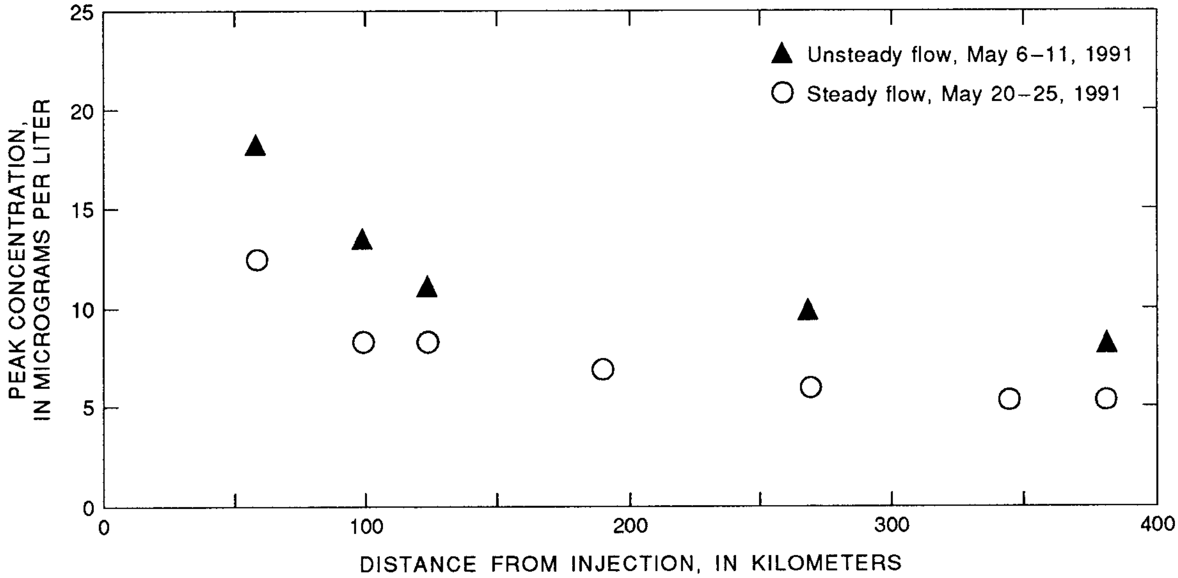

Figure 7. Relation of Peak Concentration to Distance Traveled, Grand Canyon Reach.

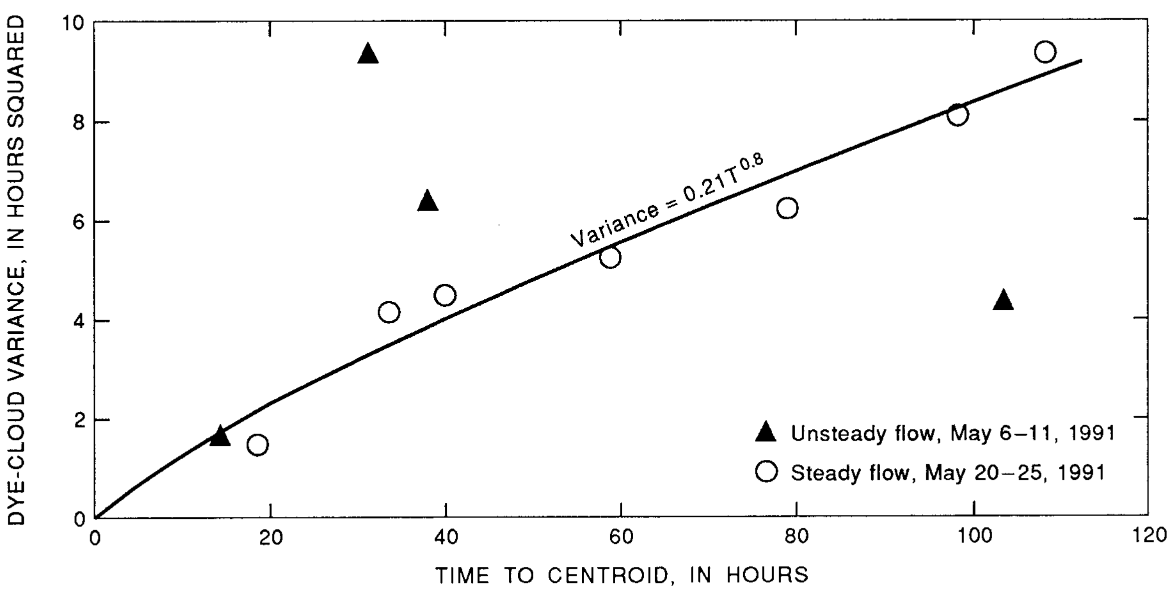

Figure 8. Relation of Dye-Cloud Variance to Traveltime of the Dye-Cloud Centroid, Grand Canyon Reach. Equation shown applies only to steady flow.

distance and traveltime during unsteady flow, but the increase was not systematic (Figure 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 *et al.*, 1989).

For the steady-flow measurement, time-concentration curves at all sites were positively skewed (Table 3 and Figure 9). Skewness decreased with time and distance, and therefore, curves are closer to normal distributions toward the downstream end of the study reach. As discussed above, skewness for sites during the unsteady-flow measurement is positive or negative, depending on the way in which discharge changed during dye passage.

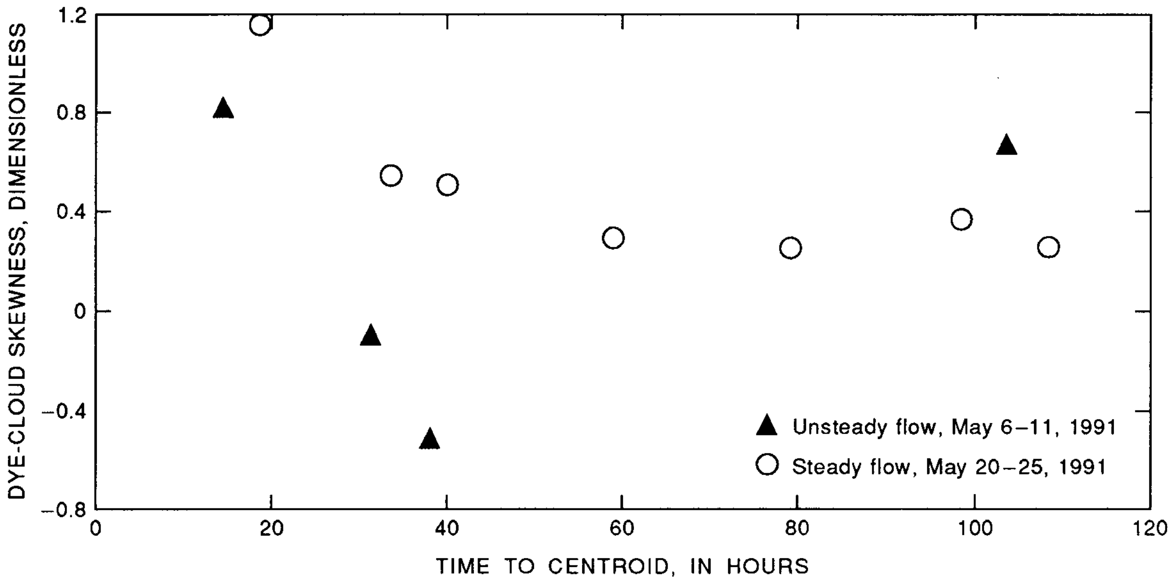

Figure 9. Relation of Dye-Cloud Skewness to Traveltime of the Dye-Cloud Centroid, Grand Canyon Reach.

PREDICTED VELOCITY AND DISPERSION FOR POTENTIAL DAM-RELEASE PATTERNS

Model Calibration

A one-dimensional unsteady-flow routing model (DAFLOW) developed by Jobson (1989) was calibrated with stage and discharge data from two research flow periods, February 1-7, 1991, and May 6-11, 1991, to provide flow information needed for solute-transport modeling. 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, and downstream from, Lees Ferry (Figure 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 at sampling sites for use in a solute-transport model.

Dye-transport data from the steady-flow measurement were used to calibrate a one-dimensional solute-transport model (BLTM) 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). Estimates of lengths required for mixing in the cross-stream direction made using the relations of Yotsukura and Cobb (1972) are small compared with the distance from the injection site to the first sampling site downstream and from the mouth of the Little Colorado River – the only major tributary to enter the study reach – to the next sampling site downstream. For this reason, and because the empirical analysis showed a one-dimensional model to fit the data reasonably well, a one-dimensional mixing model was assumed to be appropriate for this application. Results of calibration show that the one-dimensional model gives reasonable results for this application. The calibration procedure (Jobson and Schoellhamer, 1987) yielded computed time-concentration curves that fit the observed data for this study very well – mean error (computed minus observed concentration) ranged from –0.0062 to 0.073 μg/l for subreaches 3-8, downstream from Nautiloid Canyon. Root mean squared error was 0.12-0.14 μg/l for those subreaches. The reach from Lees Ferry to Nautiloid Canyon includes the initial 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 coefficients were computed from the measured time-concentration curves by the method of moments (Yotsukura *et al.*, 1970) and from model results (Table 4). Dispersion coefficients computed by the method of moments commonly differ substantially from those computed by numerical routing because the method of moments is very sensitive to the tails of the time-concentration curves, which are commonly not well defined by sampling. According to Jobson (1987), dispersion coefficients computed from model results represent the physical processes better than coefficients computed by the method of moments. The longitudinal-dispersion coefficient is computed from model results using the relation $D_f = D/(u^2dt)$, 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 numerical solution to the convective-dispersion equation in the Lagrangian reference frame 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 values of D_f less than about 0.1 (Jobson, 1987, Figure 2). The error is caused by underestimation of the concentration gradients by the model when D_f is small and fluid parcels tracked by the model are large (Jobson, 1987). For the 0.25-hour time step used for model calibration, D_f of less than 0.1 was computed for subreaches 4 and 6 (Table 4), and the model dispersion coefficients for those subreaches may have errors of 5-10 percent from this source.

Model Application

Time-concentration curves at dye sample sites in the Grand Canyon reach were estimated with the calibrated solute-transport model for three steady and two unsteady releases. The steady releases were 226 m^3/s, 425 m^3/s, and 850 m^3/s. The unsteady releases were two daily release patterns selected for evaluation as a part of the EIS process – the EIS low-fluctuating and high-fluctuating flow alternatives (Figure 10, T. J. Randle, Bureau of Reclamation, written communication, 1991). Discharge was simulated for the EIS alternatives at 0.25-hour increments for a seven-day period in July using a daily mean discharge of 425 m^3/s with 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, U.S. Geological Survey, written communication, 1992). Releases selected for modeling provide a comparison of steady releases, releases with low fluctuations, and releases with high fluctuations for the same daily mean discharge.

Results of computations with the solute-transport model indicate that velocity increases linearly with discharge for steady releases. Although measured velocity increased with discharge in the Glen Canyon reach, dispersion was much greater at the lowest measured flow than at the highest two flows measured (Figure 3). The difference between the observations in the Glen Canyon 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 lower flows.

The model predicts that velocity in individual subreaches will be higher or lower for unsteady flows than for steady flows, depending on the timing of the passage of the trough and peak of the discharge wave (Figures 2 and 11). Averaged over the entire Grand Canyon 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 degree of unsteadiness has a systematic effect on unit-peak concentration – the high-fluctuating flow alternative produces the lowest unit-peak concentration at each sampling site and

TABLE 4. Average Velocity and Longitudinal-Dispersion Coefficients at Steady Releases of 425 Cubic Meters Per Second, Grand Canyon Reach.

[Subreach 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. Average velocity was computed as velocity of the peak concentration of the model predicted time-concentration curve.]

Subreach	Length (kilometers)	Average Velocity (meters per second)	Dispersion Factor (D_f)	Longitudinal Dispersion Coefficient (square meters per second)	
				Model	Method of Moments
2	57.7	0.91	0.20	164	109
3	40.6	.79	.30	213	181
4	24.9	1.0	.06	55.1	108
5	66.1	.98	.18	159	68.1
6	78.6	1.1	.09	87.5	102
7	75.7	1.1	.20	194	202
8	36.9	1.0	.15	139	243

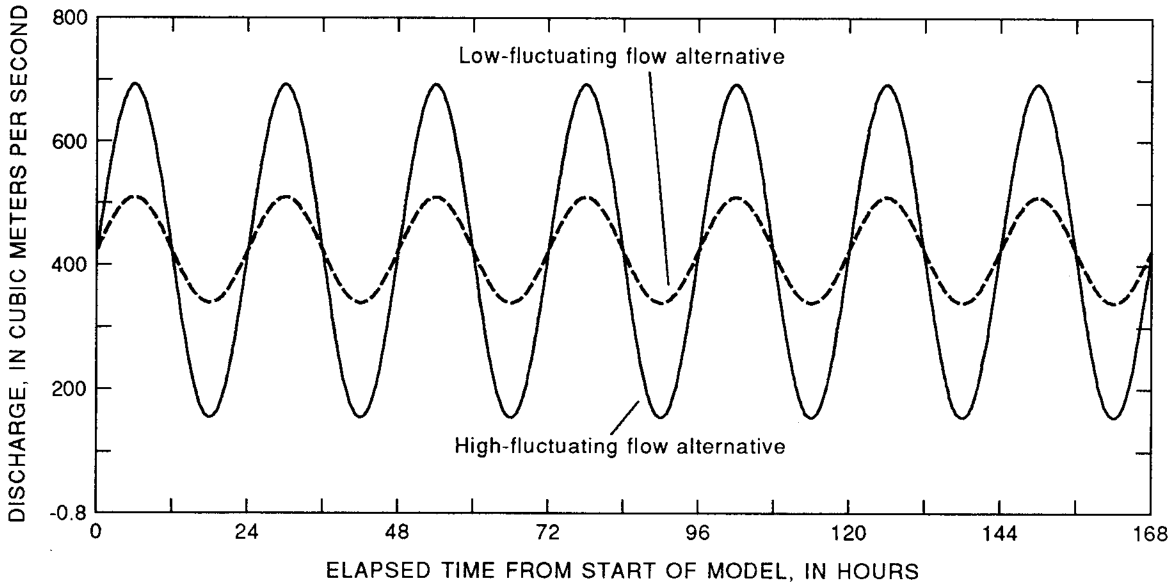

Figure 10. Discharges Simulated to Represent Two Glen Canyon Dam Environmental Impact Statement Flow Alternatives.

steady releases the highest (Figure 11). Solute-cloud duration shows a less systematic change from flow to flow. Over much of the Grand Canyon reach, little difference in duration is shown by the results (Figure 11). Solute clouds are estimated to be of shorter duration at the upstream two sites and of longer duration at the downstream end of the reach for the high-fluctuating flow alternative than for steady releases (Figure 11).

DISCUSSION AND CONCLUSIONS

Results indicate that unsteadiness of flow has little effect on flow velocity or longitudinal dispersion at the moderate mean discharge at which the Grand Canyon reach was measured in this study. Greater dye loss estimated for unsteady flow than for steady flow may be an indication that some water is temporarily stranded by decreasing stage during unsteady flow. In the Glen Canyon reach, average flow velocity varies linearly with mean discharge, but dispersion is much greater at the lowest of the three measured flows than at the two highest flows (Figure 3). Greater dispersion may be caused by increased sinuosity and longitudinal-velocity gradients that accompany the emergence of large cobble bars and riffles at low flow (140 m^3/s). Similar changes in channel geometry with discharge occur in some individual subreaches of the Grand Canyon study reach, and the low dispersion measured in the Grand Canyon reach at both steady and unsteady flow may not be indicative of dispersion during flow releases with a low daily mean discharge.

Results of this study have implications for management of dam releases to protect or enhance elements of the riparian ecosystem in the Grand Canyon. For example, the results show that the daily range of dam releases has little effect on those elements of the fluvial system that move with the fluid, such as dissolved constituents, clay-sized sediment, and fine organic material. Also, the results indicate that the rate of exchange between the eddies and the main downstream flow is high, because a slow rate of exchange would have caused greater longitudinal dispersion than was observed. The daily range of dam releases has little effect on the rate of exchange between eddies and the main flow at the moderate daily mean discharge measured in this study. If zones are present that trap water for a significant length of time, then either their volume is small enough that they have no detectable effect on fluid transport in the main channel or they are sufficiently disconnected from the main flow that very little exchange takes place. Additional evidence of high exchange rate between the main channel and slower-moving areas along the banks is given by Maddox *et al.* (1987), who found that water temperature was higher than the main channel water temperature only in backwaters that were not directly connected to the main channel.

The greater longitudinal dispersion measured at low flow (141 m^3/s) in the Glen Canyon reach may be caused by a lower exchange rate between eddies and the main flow at low flow, but it appears unlikely

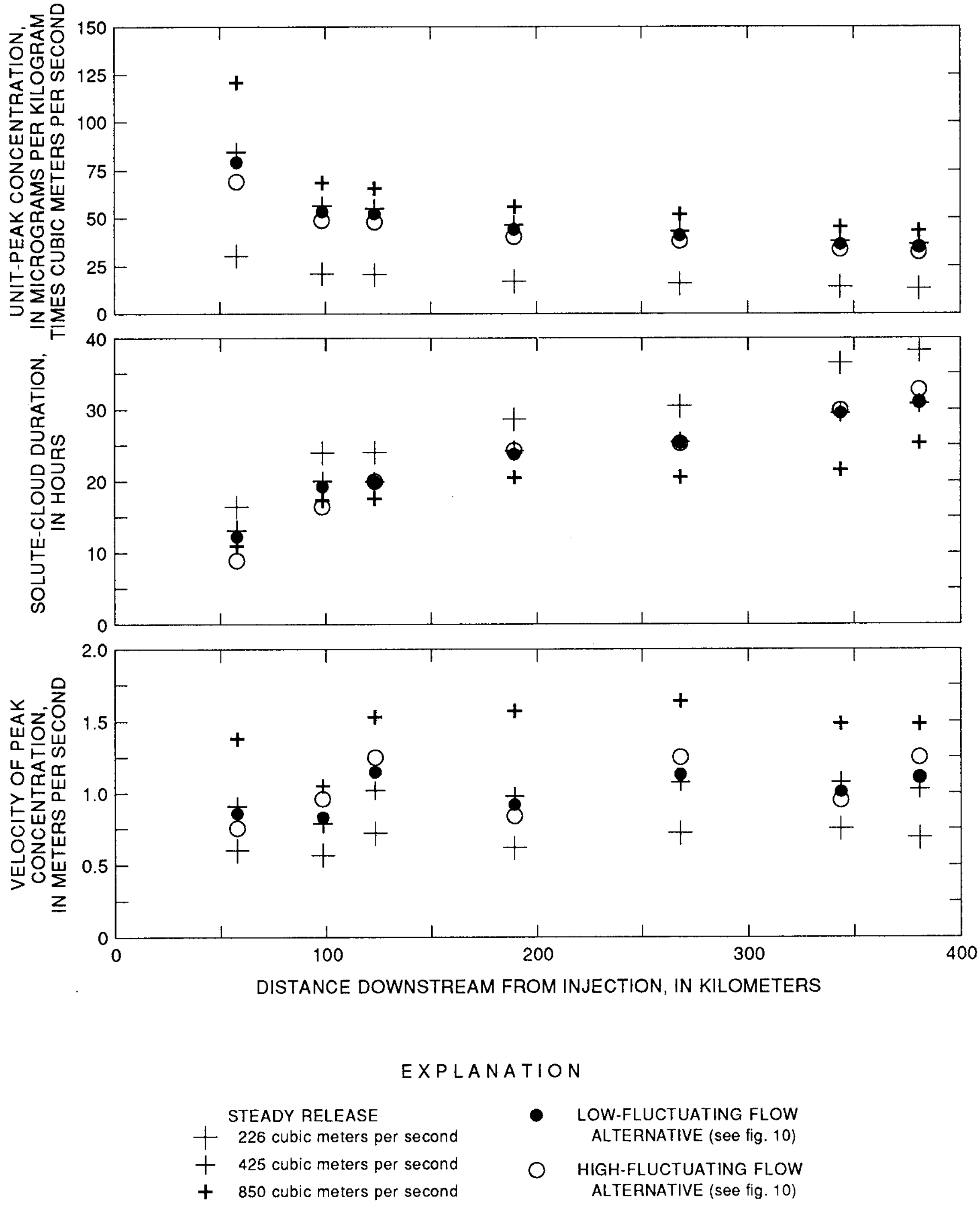

Figure 11. Relation of Unit-Peak Solute Concentration (top), Solute-Cloud Duration (middle), and Velocity of Peak Solute Concentration (bottom) Estimated by a Solute-Transport Model to Distance Downstream for Three Steady and Two Unsteady Dam Releases, Grand Canyon Reach.

that eddies can explain the observed increase in dispersion, because eddies are not as important a feature in the Glen Canyon reach as they are in the Grand Canyon reach because of differences in channel geometry and in sand supply in the two reaches.

The major conclusions of this study are as follows:

• The relation of peak concentration, dye-cloud variance, and dye-cloud duration to traveltime of the dye-cloud peak shows that longitudinal dispersion in the Grand Canyon reach is less than is commonly found in other rivers.

- The data fit a simple one-dimensional mixing model, without modifications to account for dead zones, better than data for many rivers for which measurements are available.
- 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 at the measured flows.
- Differences from subreach to subreach in large-scale channel geometry and slope have a relatively small effect on flow velocity and longitudinal dispersion.
- Unsteadiness of flow affects the velocity through individual subreaches, 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 longitudinal dispersion significantly.
- Greater longitudinal dispersion at low flow in the Glen Canyon reach may be caused by a change in the effective channel geometry. Similar channel-geometry changes probably also cause greater dispersion at low flows than at high flows in at least some of the individual subreaches in the Grand Canyon reach.
- 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.

ACKNOWLEDGMENTS

The study was done in cooperation with the Bureau of Reclamation and funding was provided through the Glen Canyon Environmental Studies. OARS, Inc., Angels Camp, California, provided logistical support for the field measurements – Mike Walker coordinated the support effort; Randy Fabres and Tim Deutschlander were the boatmen during the Grand Canyon measurements; and Denise Hogan, K.C. Deutschlander, and Monte Becker provided meals and other logistic support. Hatch Expeditions, Marble Canyon, Arizona, provided a raft and boatman used for one dye injection in the Grand Canyon reach. 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. James F. Wilson, Jr. and Hjalmar W. Hjalmarson, U.S. Geological Survey, and Prof. Zdzislaw Mikulski and Dr. Artur Magnuszewski, Warsaw University, reviewed the report and made suggestions that improved it.

LITERATURE CITED

Bencala, K. E. and R. A. Walters, 1983. Simulation of Solute Transport in a Mountain Pool-and-Riffle Stream – A Transient Storage Model. Water Resources Research 19(3):718-724.

Day, T. J., 1975. Longitudinal Dispersion in Natural Channels. Water Resources Research 11(6):909-918.

Fischer, H. B., 1973. Longitudinal Dispersion and Turbulent Mixing in Open-Channel Flow. Annual Review of Fluid Mechanics 5:59-78.

Godfrey, R. G. and B. J. Frederick, 1970. Stream Dispersion at Selected Sites. U.S. Geological Survey Professional Paper 433-K, 38 pp.

Graf, J. B., 1986. Traveltime and Longitudinal Dispersion in Illinois Streams. U.S. Geological Survey Water-Supply Paper 2269, 65 pp.

Howard, Alan and Robert Dolan, 1981. Geomorphology of the Colorado River in the Grand Canyon. Journal of Geology 89(3):269-298.

Hubbard, E. F., F. A Kilpatrick, L. A. Martens, and J. E. Wilson, 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, Chapter A9, 44 pp. [in part superseded by Kilpatrick and Wilson, 1989].

Jobson, H. E., 1987. Estimation of Dispersion and First-Order Rate Coefficients by Numerical Routing. Water Resources Research 23(1):169-180.

Jobson, H. E., 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 pp.

Jobson, H. E. and D. H. Schoellhamer, 1987. Users Manual for a Branched Lagrangian Transport Model. U.S. Geological Survey Water-Resources Investigations Report 87-4163, 73 pp.

Kilpatrick, F. A., 1972. Automatic Sampler for Dye Tracer Studies. Water Resources Research 8(3):737-742.

Kilpatrick, F. A., R. E. Rathbun, Nobuhiro Yotsukura, G. W. Parker, and L. L. DeLong, 1989. Determination of Stream Reaeration Coefficients by use of Tracers. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A18, 52 pp.

Kilpatrick, F. A. and K. R. Taylor, 1986. Generalization and Applications of Tracer Dispersion Data. Water Resources Bulletin 22(4):537-548.

Kilpatrick, F. A. and J. F. Wilson, Jr., 1989. Measurement of Time of Travel in Streams by Dye Tracing. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A9, 27 pp.

Maddox, H. R., D. M. Kubly, J. C. deVos, Jr., W. R. Persons, Richard Staedicke, and R. L. Wright, 1987. Effects of Varied Flow Regimes on Aquatic Resources of Glen and Grand Canyons. Final Report, Arizona Game and Fish Department, Phoenix, Arizona, 291 pp.

National Research Council, 1987. River and Dam Management – A Review of the Bureau of Reclamation's Glen Canyon Environmental Studies. National Research Council, Water Science and Technology Board, 203 pp.

Nordin, C. F., Jr. and G. V. Sabol, 1974. Empirical Data on Longitudinal Dispersion in Rivers. U.S. Geological Survey Water-Resources Investigations Report 20-74, 332 pp.

Schmidt, J. C., 1990. Recirculating Flow and Sedimentation in the Colorado River in Grand Canyon, Arizona. Journal of Geology 98:709-724.

Schmidt, J. C. and J. B. Graf, 1990. Aggradation and Degradation of Alluvial Sand Deposits, 1965 to 1986, Colorado River, Grand Canyon, Arizona. U.S. Geological Survey Professional Paper 1493, 74 pp.

Seo, I. W., 1990. Laboratory and Numerical Investigation of Longitudinal Dispersion in Open Channels. Water Resources Bulletin 26(5):811-822.

U.S. Department of the Interior, 1989. Glen Canyon Environmental Studies Final Report. Bureau of Reclamation, Upper Colorado Region, Salt Lake City, 84 pp. + appendices (NTIS No. PB88-183348/AS).

Valentine, E. M. and I. R. Wood, 1977. Longitudinal Dispersion with Dead Zones. American Society of Civil Engineers, Journal of the Hydraulics Division 103:975-990.

Wilson, J. F., Jr., E. D. Cobb, and F. A. Kilpatrick, 1986. Fluorometric Procedures for Dye Tracing (revised). U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A12, 31 pp.

Wilson, R. P., 1986. Sonar Patterns of Colorado Riverbed, Grand Canyon. *In:* Proceedings of the Fourth Federal Interagency Sedimentation Conference, 1986. Subcommittee on Sedimentation of the Interagency Committee on Water Data, pp. 5-133 to 5-142.

Yotsukura, Nobuhiro and E. D. Cobb, 1972. Transverse Diffusion of Solutes in Natural Streams. U.S. Geological Survey Professional Paper 582-C, 19 pp.

Yotsukura, Nobuhiro, H. B. Fischer, and W. W. Sayre, 1970. Measurement of Mixing Characteristics of the Missouri River Between Sioux City, Iowa, and Plattsmouth, Nebraska. U.S. Geological Survey Water-Supply Paper 1899-G, 29 pp.