Stage-Discharge Relations for the Colorado River in Glen, Marble, and Grand Canyons, Arizona, 1990-2005

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Prepared in cooperation with Northern Arizona University

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)

In this report, horizontal and vertical coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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Abstract

This report presents stage-discharge relations for 47 discrete locations along the Colorado River, downstream from Glen Canyon Dam. Predicting the river stage that results from changes in flow regime is important for many studies investigating the effects of dam operations on resources in and along the Colorado River. The empirically based stage-discharge relations were developed from water-surface elevation data surveyed at known discharges at all 47 locations. The rating curves accurately predict stage at each location for discharges between 141 cubic meters per second and 1,274 cubic meters per second. The coefficient of determination (R^2) of the fit to the data ranged from 0.993 to 1.00. Given the various contributing errors to the method, a conservative error estimate of ±0.05 m was assigned to the rating curves.

Introduction

Closure of Glen Canyon Dam in 1963 dramatically altered the flow regime of the Colorado River in Grand Canyon National Park (GCNP) (U.S. Department of Interior, 1995). The pre-dam flow regime exhibited large annual fluctuations and small daily variations. Operations of the dam intentionally cause daily fluctuations for hydropower generation, while annual flow fluctuations are now substantially reduced. Although seasonal variations in the hydrograph have been flattened, daily discharge fluctuations generally occur over a much greater range than in the pre-dam era (Topping and others, 2003). The altered hydrograph has important consequences for the geomorphology and ecology of the Colorado River in GCNP, and the downstream riverine ecosystem is now the subject of a large-scale rehabilitation program called the Glen Canyon Adaptive Management Program (National Research Council, 1999). As part of this program, flow experiments are undertaken to benefit downstream resources.

The experimental designs proposed and implemented in the Glen Canyon Adaptive Management Program have increased the need to predict river stage at particular locations. Stage ranges and inundation levels are important for their potential effect on a wide variety of ecosystem components. In 1990, Northern Arizona University, in cooperation with the U.S. Bureau of Reclamation's Glen Canyon Environmental Studies (U.S. Department of Interior, 1995), began a project of surveying sandbars located along the Colorado River in GCNP (fig. 1). As part of this project, stage-discharge rating curves were developed by Northern Arizona University, in cooperation with the U.S. Geological Survey, from numerous surveys of water-surface elevation at known discharges. The rating curves have been used to (1) quantify changes in sandbar area and volume within specific stage elevation ranges (Kaplinski and others, 1995; Hazel and others, 1999; Hazel and others, 2006), (2) determine camping area as a function of stage elevation (Kaplinski and others, 2005), (3) calibrate ground water models (Springer and others, 1999; Sabol and Springer, 2005), (4) check the accuracy and set boundary conditions of hydraulic models that predict shoreline water-surface elevations (Magirl and Breedlove, 2005; Wiele and Torrizo, 2003; Wiele and Torrizo, 2005); (5) predict flood-stage elevations and inundation levels at archeological sites (Draut and others, 2005), (6) determine impacts to habitat and associated endangered Kanab Ambersnail populations (Meretsky and others, 2000; Cox and others, 2005), (7) examine trout spawning-habitat preference as a function of discharge (Korman and others, 2005), and (8) investigate near-shore water temperatures (Korman and others, 2006).

Purpose and Scope

The purpose of this report is to present stage-discharge relations for 47 discrete locations in the Colorado River downstream from Glen Canyon Dam to Diamond Creek, Ariz (table 1). The report describes an empirically based method of formulating stage-discharge relations by using surveys of water-surface elevations at known discharges. The results are of value for the prediction and execution of field experiments and other analyses of ecosystem responses to dam operations. The stage range of the relations is limited to the highest discharge in cubic meters per second (1,274 m^3/s) observed during the study period, 1990-2005. The rating curves presented in this report predict local stage accurately, but are site-specific and cannot be applied elsewhere. In addition, infrequent rockfall or debris flows that alter channel geometry and river hydraulics can potentially alter the stage-discharge relations and by necessity will have to be accounted for.

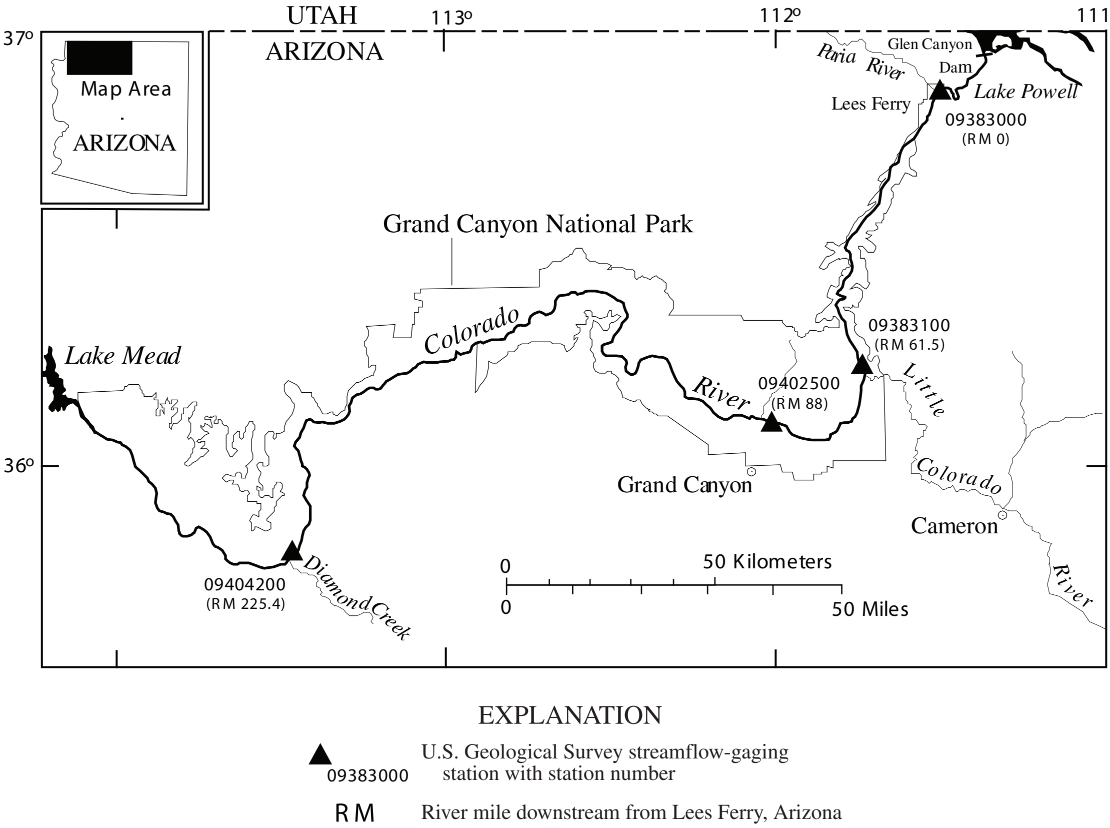

Figure 1. Study area, major tributaries and locations of U.S. Geological Survey continuous-record streamflow-gaging stations, Colorado River, Glen Canyon Dam to upper Lake Mead, Arizona.

Acknowledgments

We thank Grand Canyon National Park and Glen Canyon National Recreation area for permission to access study sites along the Colorado River. Numerous people provided field assistance, but we thank Eric Kellerup and Greg Sponenburgh in particular. The manuscript benefited from technical reviews by Amy Draut and Stephen Wiele, and thorough editorial reviews and revisions by Cathy Rubin and Keith Lucey.

Physical Setting

Locations on the Colorado River are traditionally defined by the river mile (RM) downstream from Lees Ferry, Arizona (RM 0). In this report, study sites are referred to by river mile location along the river centerline developed by the USGS Grand Canyon Monitoring and Research Center (U.S. Geological Survey, 2006). This river mile centerline was developed in a geographic information system (GIS) and is considered more accurate than previous river-mile estimates. One site is located in Glen Canyon, the reach between Glen Canyon Dam and Lees Ferry (RM -15 to 0). Twenty-one sites are located in Marble Canyon, the reach between Lees Ferry and the confluence with the Little Colorado River (RM 0 to 61.7). Twenty-five sites are located in Grand Canyon, between the confluence with the Little Colorado River and Diamond Creek (RM 226). The study area includes four U.S. Geological Survey (USGS) streamflow-gaging stations (fig. 1). The streamflow-gaging stations utilized for this report are located at Lees Ferry (RM 0; station number 09380000), above the confluence with the Little Colorado River (RM 61.5; 09381000, discontinued in 2002), Grand Canyon near Phantom Ranch (RM 88; 09402500), and above the confluence with Diamond Creek near Peach Springs (RM 225.4; 09404200).

The longitudinal profile of the Colorado River includes shallow areas at rapids and riffles and deep pools that typically occur upstream and downstream from rapids (Leopold, 1969). Rapids are commonly located where talus deposits and tributary debris fans constrict the river channel. Longitudinal variation in channel and valley width varies in relation to the erodibility of the bedrock exposed at river level (Howard and Dolan, 1981). The average water-surface gradient is 0.0015 between Lees Ferry and Diamond Creek and ranges from less than 0.0005 in pools to greater than 0.01 in rapids (Schmidt and Graf, 1990). Water-surface slope flattens in pools and recirculation zones (or eddies) located upstream and downstream from rapids. The study sites were focused on sandbars located in eddies where water-surface elevations are near horizontal. The upstream and downstream length of channel to which each stage-discharge relation can apply is shown in table 1.

Table 1. Site names, locations, and stage-discharge relations, Colorado River, Glen Canyon Dam to Diamond Creek, Arizona

[Site names are given by location along the river mile (RM) centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry, in Grand Canyon National Park except, -6.5R, which is in Glen Canyon National Recreation Area. L and R refer to the left and right bank as viewed in a downstream direction, respectively; extent, channel reach to which stage-discharge relation applies; Z, height in meters above the Geodetic Reference System of 1980/North American Datum of 1983 ellipsoid; Q, discharge; m^3/s, cubic meters per second; the predicted stage change is given for the difference in water-surface elevation for discharges between 142 m^3/s and 1,274 m^3/s, in meters (m)]

Site Name (RM)	Upstream Extent (RM)	Downstream Extent (RM)	Stage-Discharge Relation, Q in m^3/s	Stage Change (m)
-6.5R	-6.70	-6.50	$Z = 927.2345 + 0.0046Q - 9.7557\text{x}10^{-7}Q^{2}$	3.64
1.2R	1.10	1.30	$Z = 920.1800 + 0.0058Q - 1.8793\text{x}10^{-6}Q^{2}$	3.53
2.6L	2.48	2.68	$Z = 919.5346 + 0.0060Q - 1.7549\text{x}10^{-6}Q^{2}$	3.99
8.2L	8.10	8.35	$Z = 912.7481 + 0.0035Q - 2.6250\text{x}10^{-6}Q^{2}$	3.51
16.7L	16.65	16.8	$Z = 894.5953 + 0.0052Q - 1.4169\text{x}10^{-6}Q^{2}$	3.61
22.0R	21.05	22.08	$Z = 878.4473 + 0.0103Q – 3.0524\text{x}10^{-6}Q^{2}$	6.76
23.6L	23.53	23.65	$Z = 873.8798 + 0.0099Q - 3.3402\text{x}10^{-6}Q^{2}$	5.86
29.5L	29.43	29.55	$Z = 856.3392 + 0.0084Q - 2.4403\text{x}10^{-6}Q^{2}$	5.65
30.8R	30.68	30.82	$Z = 853.6511 + 0.0085Q - 2.3554\text{x}10^{-6}Q^{2}$	5.83
31.9R	31.85	32.05	$Z = 853.0456 + 0.0049Q - 1.3643\text{x}10^{-6}Q^{2}$	3.41
32.2R	32.18	32.21	$Z = 852.2250 + 0.0043Q - 4.5342\text{x}10^{-7}Q^{2}$	4.12
33.3L	33.15	33.30	$Z = 849.1904 + 0.0065Q - 1.1068\text{x}10^{-6}Q^{2}$	5.53
35.1L	35.03	35.20	$Z = 846.3659 + 0.0090Q - 2.7067\text{x}10^{-6}Q^{2}$	5.87
41.3L	41.20	41.52	$Z = 839.6944 + 0.0059Q - 1.1409\text{x}10^{-6}Q^{2}$	4.84
43.4L	43.37	43.47	$Z = 838.3170 + 0.0072Q - 1.9473\text{x}10^{-6}Q^{2}$	4.98
44.5L	44.40	44.72	$Z = 835.5083 + 0.0066Q - 1.6682\text{x}10^{-6}Q^{2}$	4.76
45.0L	44.87	45.03	$Z = 835.2158 + 0.0051Q - 6.9759\text{x}10^{-7}Q^{2}$	4.63
47.6R	47.50	47.75	$Z = 833.0905 + 0.0059Q - 1.5676\text{x}10^{-6}Q^{2}$	4.13
50.2R	50.10	50.25	$Z = 829.1319 + 0.0064Q - 1.6577\text{x}10^{-6}Q^{2}$	4.59
51.5L	51.32	51.57	$Z = 828.5607 + 0.0061Q - 1.7551\text{x}10^{-6}Q^{2}$	4.09
55.9R	55.80	56.00	$Z = 819.3199 + 0.0044Q - 1.2732\text{x}10^{-6}Q^{2}$	2.93
56.6R	56.50	56.57	$Z = 816.6207 + 0.0044Q - 1.1396\text{x}10^{-6}Q^{2}$	3.19
62.9R	62.82	62.98	$Z = 799.8819 + 0.0059Q - 1.3166\text{x}10^{-6}Q^{2}$	4.56
65.2R	65.08	65.30	$Z = 795.7844 + 0.0043Q - 9.7169\text{x}10^{-7}Q^{2}$	3.33
66.1L	66.03	66.25	$Z = 793.6146 + 0.0042Q - 1.4984\text{x}10^{-7}Q^{2}$	2.37
68.8R	68.65	68.90	$Z = 786.0775 + 0.0041Q - 1.1667\text{x}10^{-6}Q^{2}$	2.81
81.7L	81.73	81.78	$Z = 735.9746 + 0.0059Q - 1.4777\text{x}10^{-6}Q^{2}$	4.35
84.6R	84.50	84.60	$Z = 724.6525 + 0.0062Q - 1.1833\text{x}10^{-6}Q^{2}$	5.15
87.6L	87.50	87.68	$Z = 716.0649 + 0.0075Q - 2.5026\text{x}10^{-6}Q^{2}$	4.50
88.1R	88.00	88.13	$Z = 716.3174 + 0.0059Q - 1.6647\text{x}10^{-6}Q^{2}$	3.96
91.8R	91.72	91.80	$Z = 699.4004 + 0.0064Q - 1.4437\text{x}10^{-6}Q^{2}$	4.93
93.8L	93.75	93.86	$Z = 696.9266 + 0.0057Q - 1.8772\text{x}10^{-6}Q^{2}$	3.44

Table 1. Site names, locations, and stage-discharge relations, Colorado River, Glen Canyon Dam to Diamond Creek, Arizona—Continued

[Site names are given by location along the river mile (RM) centerline (U.S. Geological Survey, 2006) downstream from Lees Ferry, in Grand Canyon National Park except, -6.5R, which is in Glen Canyon National Recreation Area. L and R refer to the left and right bank as viewed in a downstream direction, respectively; extent, channel reach to which stage-discharge relation applies; Z, height in meters above the Geodetic Reference System of 1980/North American Datum of 1983 ellipsoid; Q, discharge; m^3/s, cubic meters per second; the predicted stage change is given for the difference in water-surface elevation for discharges between 142 m^3/s and 1,274 m^3/s, in meters (m)]

Site Name (RM)	Upstream Extent (RM)	Downstream Extent (RM)	Stage-Discharge Relation, Q in m^3/s	Stage Change (m)
104.4R	104.35	104.45	$Z = 658.3761 + 0.0066Q - 1.8602\ \mathrm{x}10^{-6}Q^2$	4.51
119.4R	119.33	119.45	$Z = 613.6991 + 0.0072Q - 1.7671\mathrm{x}10^{-6}Q^2$	5.33
122.7R	122.70	122.80	$Z = 607.9881 + 0.0073Q - 2.1437\mathrm{x}10^{-6}Q^2$	4.80
123.3L	123.17	123.30	$Z = 607.2691 + 0.0078Q - 2.5742\mathrm{x}10^{-6}Q^2$	4.70
137.7L	137.65	137.72	$Z = 562.4849 + 0.0067Q - 1.8079\mathrm{x}10^{-6}Q^2$	5.55
139.6R	139.50	139.66	$Z = 557.1314 + 0.0075Q - 2.0031\mathrm{x}10^{-6}Q^2$	5.27
145.8L	145.83	145.90	$Z = 539.8538 + 0.0083Q - 2.2142\mathrm{x}10^{-6}Q^2$	5.83
167.2L	167.10	167.25	$Z = 505.4650 + 0.0051Q - 9.7770\mathrm{x}10^{-7}Q^2$	4.23
172.6L	172.50	172.70	$Z = 497.2574 + 0.0061Q - 1.4370\mathrm{x}10^{-6}Q^2$	4.55
183.3R	183.20	183.38	$Z = 470.1667 + 0.0069Q - 1.8743\mathrm{x}10^{-6}Q^2$	4.84
194.6L	194.50	194.70	$Z = 446.8107 + 0.0064Q - 1.7595\mathrm{x}10^{-6}Q^2$	4.44
202.3R	202.30	202.48	$Z = 431.4507 + 0.0059Q - 1.3866\mathrm{x}10^{-6}Q^2$	4.46
213.3L	213.30	213.28	$Z = 403.5871 + 0.0096Q - 2.5109\mathrm{x}10^{-6}Q^2$	6.80
220.1R	220.05	220.12	$Z = 394.3845 + 0.0039Q - 5.3231\mathrm{x}10^{-7}Q^2$	3.54
225.5R	225.40	225.60	$Z = 380.6412 + 0.0065Q - 2.4598\mathrm{x}10^{-6}Q^2$	3.45

Data and Method Used in Formulating Stage-Discharge Relations

Streamflow-Gaging Data

Discharge measurements at the USGS continuous-record streamflow-gaging stations were used to determine discharge at each study site. The USGS uses a standard method of computing discharge by developing a stage-discharge rating curve to convert measured stage to discharge (Rantz and others, 1982). The method employs numerous flow velocity measurements and surveyed cross sections at each gage to construct a stage-discharge relation. The accuracies of the continuous-record streamflow-gaging stations in the study area, for the period of study, are considered “good,” which means that 95 percent of the daily mean discharges are within 10 percent of true (McCormack and others, 2003).

Water-Surface Elevations

Water-surface elevations (high and low watermarks from peak and trough discharges, and strandlines from tributary and controlled floods) were surveyed with optical total stations located on geodetic control network benchmarks. The benchmarks were referenced to National Spatial Reference System (NSRS) control stations (Doyle, 1994) located along the canyon rim by using static Global Positioning System (GPS) techniques. GPS observations yield heights above the ellipsoid defined by the Geodetic Reference System of 1980 (GRS80) and the North American Datum of 1983 (NAD83). In this report, ellipsoidal heights have not been converted to North American Vertical Datum of 1988 (NAVD88) orthometric heights because the current national geoid model (GEOID03) does not incorporate sufficient gravity measurements in the region to account for the effects of topography (mass/ void) on height measurements. As a result, spatial data collected for resource monitoring in GCNP is, at this time, referenced to the NAD83 ellipsoid (Saleh and others, 2003). When an accurate geoid model of the study area is produced, the stage-discharge relations in this report can readily be converted to NAVD88 orthometric heights.

The control network benchmarks have positioning accuracies of less than 0.03 meter (m) and ellipsoidal height accuracies of between 0.01 and 0.10 m at 95 percent confidence (Zilkoski and others, 1997). Precision of optical measurements is 0.05 m or better. Points collected along the water surface or along strand lines corresponded to an average density of one point per 1 to 2 linear meters. After verification of positions and heights, the point data were converted to mean values for the stage elevations of interest. The range of elevation differences was typically less than 0.10 m, and standard deviations were at or better than 0.03 m.

Computation of Stage-Discharge Relations

Stage-discharge relations were empirically developed for each site by compiling the stage data and assigning a discharge to each mean elevation by comparing steady discharges and daily peak and trough discharges from the nearest streamflow-gaging station upstream or downstream from each site. Water-surface elevations surveyed during the rising or falling limb of the diurnal discharge wave were discarded. As a result, there was no need to route the relevant portions of the Glen Canyon Dam discharge record to the location of study by using the one-dimensional, unsteady-flow model of Wiele and Griffin (1997). Substantial differences in trough and peak discharges between streamflow-gaging stations were accounted for by interpolating the values between gages. Fitting a line to the data by using a second-order polynomial leads to a stage-discharge relation for a particular site as:

$$Z = C0 + C1Q + C2Q^2, \qquad (1)$$

where Z is stage in meters, C0, C1, and C2 are polynomial coefficients referenced to NAD83 ellipsoid height, and Q is discharge in cubic meters per second. With the data available, this equation yields a rating curve for discharges between142 m^3/s and 1,274 m^3/s (fig. 2). The coefficient of determination (R^2) of the fit to the data ranged from 0.993 to 1.00. The rating curves and their applicable locations along the river are shown in table 1.

The stage change predicted by the relations varies considerably between sites. The smallest stage change between 142 m^3/s and 1,274 m^3/s is 2.37 m at RM 66.1L, whereas the greatest stage change for this same difference in discharge is 6.80 m at RM 213.3L (table 1). Because of the nature of the polynomial fit, extrapolation of the relations for discharges greater than 1,274 m^3/s will yield erroneous values. In addition, to use the stage-discharge relation for discharge data in cubic feet per second, the data must first be converted to cubic meters per second.

Possible sources of error with this method are the effects of wave attenuation, evaporation, inflow from springs, or water released from bank storage between the streamflow-gaging stations and each site of interest. However, the difference in rating curves between any two gaging stations is less than 5 percent during periods of little or no ungaged-tributary input, and, for the purposes of this report, these factors are negligible. Ungaged-tributary inflow was accounted for by solely utilizing the downstream gaging station from the site of interest. Given these independent sources of error and the error associated with optical total station surveys, a conservative error estimate of ±0.05 m was assigned to the rating curves in this report.

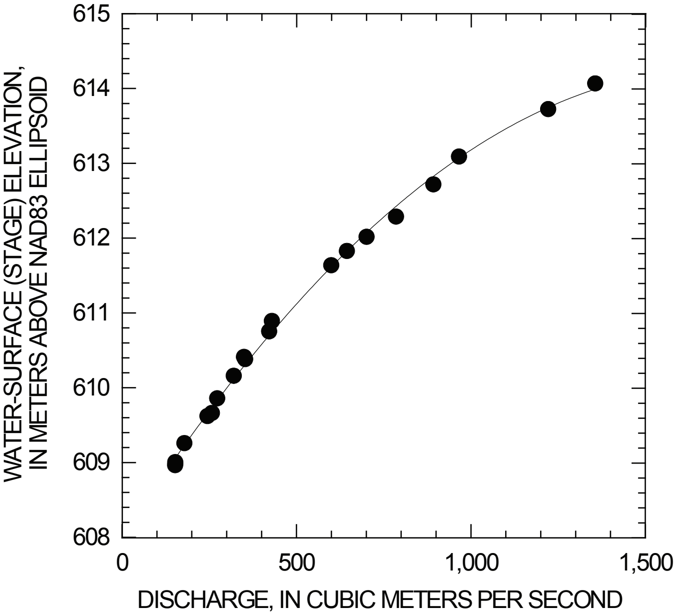

Figure 2. Stage-discharge relation for the study site located at river mile 122.7R.

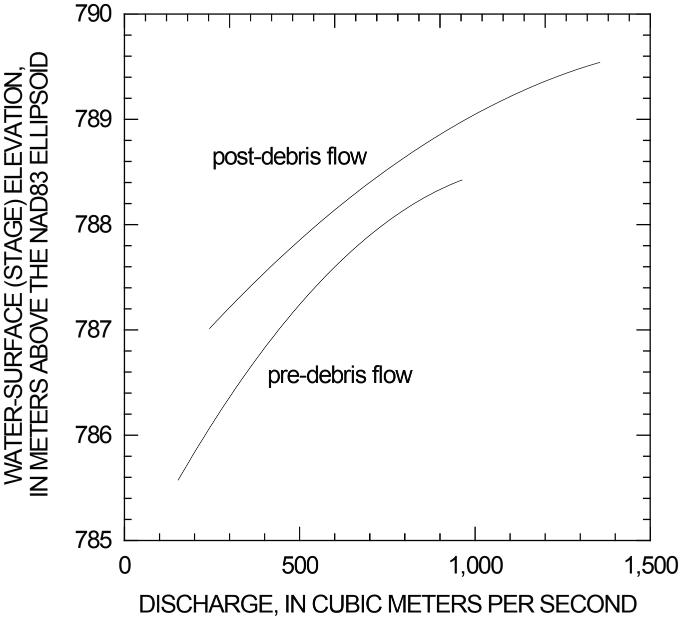

Figure 3. Stage-discharge relations for the study site located at river mile 68.8R, showing the relations computed prior to and following a debris flow in Tanner Wash on August 20, 1993.

Local changes in the stage-discharge relations can be caused by changes in the channel constriction due to debris flows and rockfalls (fig. 3). During the period of study there were two debris flow-induced changes in channel geometry that caused substantial changes in the nearby stage-discharge relation. The first was a debris flow in Tanner Wash on August 20, 1993 (Melis and others, 1994) that increased the water-surface elevation of the pool upstream from Tanner Rapid (RM 69.0) by about 1.2 m at a discharge of 227 m^3/s (fig. 3). The second was a debris flow in Lava Canyon (RM 65.8R) on September 11, 2002 that increased the water-surface elevation of the pool upstream from Lava Canyon Rapid (stage-discharge relation at RM 65.2R) by 0.3-0.5 m. Future debris flows in tributaries to the Colorado River could potentially cause hydraulic and geomorphic changes that would affect the stage-discharge relations described in this report.

Summary

Stage data collected from 1990-2005 were used to develop stage-discharge relations at 47 locations along the Colorado River in Glen, Marble, and Grand Canyons. The stage data were compiled and assigned discharge values by comparing steady discharges and daily peak and trough discharges from the nearest streamflow-gaging station, upstream or downstream from each site. A second-order polynomial was fit to the data yielding a rating curve for each site. The rating curves accurately predict stage within ±0.05 m, for discharges ranging from 141 m^3/s to 1,274 m^3/s. The stage change at the sites varied from 2.37 m to 6.80 m for this range of discharge. The relations are convenient to use and require no additional information to produce a stage prediction at a given location. Because of the nature of the polynomial fit, however, the relations are not suited for predicting river stages greater than 1,274 m^3/s. In order to use the stage-discharge relation for discharge data in cubic feet per second the data must first be converted to cubic meters per second.

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