COMPARISON, ANALYSIS, AND ESTIMATION OF DISCHARGE DATA FROM TWO ACOUSTIC VELOCITY METERS ON THE CHICAGO SANITARY AND SHIP CANAL AT ROMEOVILLE, ILLINOIS

by Charles S. Melching and Kevin A. Oberg

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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ABSTRACT

Acoustic velocity meters (AVM's) were installed on the Chicago Sanitary and Ship Canal at Romeoville, Ill., to aid in the accounting of water diverted from Lake Michigan to the Illinois River. This report describes the analyses performed to establish the most accurate estimates of discharge possible at this time on the Canal at Romeoville for water years 1986 through 1991 (October 1985-September 1991). The first AVM at Romeoville was operational on June 12, 1984. On November 3, 1988, the AVM was shut down because of numerous maintenance problems; on November 17, 1988, it was replaced by an AVM made by another manufacturer. The AVM's were and are occasionally rendered inoperative because of power surges, damage by barges, and other causes. During these periods of AVM inoperation, discharge estimates made by the Metropolitan Water Reclamation District of Greater Chicago (MWRD) at the Lockport powerhouse, lock, and controlling works are used to approximate the flow at Romeoville through a series of estimation equations that are updated and improved as described in this report.

Naturally caused differences in discharges between the period of operation of the first and second AVM's are far greater than any differences that may be attributed to the performance of the two AVM's. The regression equations relating AVM discharge estimates at Romeoville with MWRD discharge estimates at Lockport for the period of operation were comparable. The accuracy of the simulated data set is nearly the same as the best-fit regression equations. The vertical velocity-distribution measurements made by the two AVM's are consistent and are within the range of values expected from open-channel flow theory. Therefore, no difference in the discharge computed using the two AVM's can be supported, and no correction factor is needed to adjust one AVM to be consistent with the other.

Two different forms of equations for estimating discharge at Romeoville on the basis of MWRD discharge estimates at Lockport were compared. The first form was from standard multiple-linear regression between AVM discharge estimates at Romeoville and MWRD estimates of discharge at Lockport through the various outlet components--turbines, lockage, and leakage; powerhouse sluice gates; and controlling works. In the second form, the regression relation between MWRD estimates of turbine, lockage, and leakage (TLL) discharge at Lockport and AVM discharge estimates at Romeoville derived for days when the sluice gate and (or) controlling works were not in operation was used to define an error relation for the TLL discharge regime. This error relation was used to determine corrected

discharges through the sluice gates and (or) controlling works. Regression equations were derived relating the corrected discharges and the MWRD estimates of discharge through these outlet components. The equations derived from corrected discharges performed as well as the first form of regression equations in terms of closeness of fit for the calibration period and estimation quality for the verification period. The equations derived from corrected discharges estimated the mean, standard deviation, and skewness coefficient of the daily mean discharges at Romeoville for the verification period within 0.22, 5.15, and 0.66 percent, respectively. The equations derived from the corrected discharges were used to estimate discharge at Romeoville for days when the AVM was not operational because of their strong physical basis and excellent verification results.

The AVM discharge estimates were adjusted for the width and depth errors that were detected during a 1991 canal survey, and the discharge was estimated using the equations derived from corrected discharges for the 545 days on which the AVM was not operational. The final best estimates of discharge have been entered into the discharge record for the station.

INTRODUCTION

The modified U.S. Supreme Court Decree of December 1, 1980, limits the diversion of water from Lake Michigan by the State of Illinois and the city of Chicago to a 40-year average of 3,200 ft^3/s with the cumulative algebraic sum of the average annual diversions minus 3,200 ft^3/s during the first 39 years to be no more than 2,000 ft^3/s-years. The U.S. Army Corps of Engineers, Chicago District (Corps), has been charged with the diversion accounting. As part of the accounting procedure, the Supreme Court ordered the Corps to convene a three-member Technical Committee at least every 5 years to review the accounting procedure and to ensure that the accounting procedure is "state of the art."

The acoustic velocity meter (AVM) on the Chicago Sanitary and Ship Canal at Romeoville, Ill. (fig. 1), is a key part of the Lake Michigan diversion-accounting procedure. The operation and maintenance of the AVM is the responsibility of the U.S. Geological Survey (USGS) by agreement with the Corps. The AVM operates on the principle that point-to-point traveltime of an acoustic signal is greater when the signal is traveling upstream than when traveling downstream. The difference in traveltime is due to the motion of the water relative to the transducers that receive the acoustic signals. Thus, the AVM can be used to determine the average velocity across the width of the canal for a given elevation (path). The instantaneous average velocity and discharge can be computed by placing transducers at several elevations to represent the variation of velocity with depth. The acoustic signals from the AVM installation at Romeoville are directed in three paths downstream and in one cross path upstream (fig. 2).

The first AVM at Romeoville, manufactured by Sarasota Automation,[1] was installed during the week of March 18-23, 1984, and became operational on June 12, 1984. On November 3, 1988, the Sarasota AVM was shut down because of

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

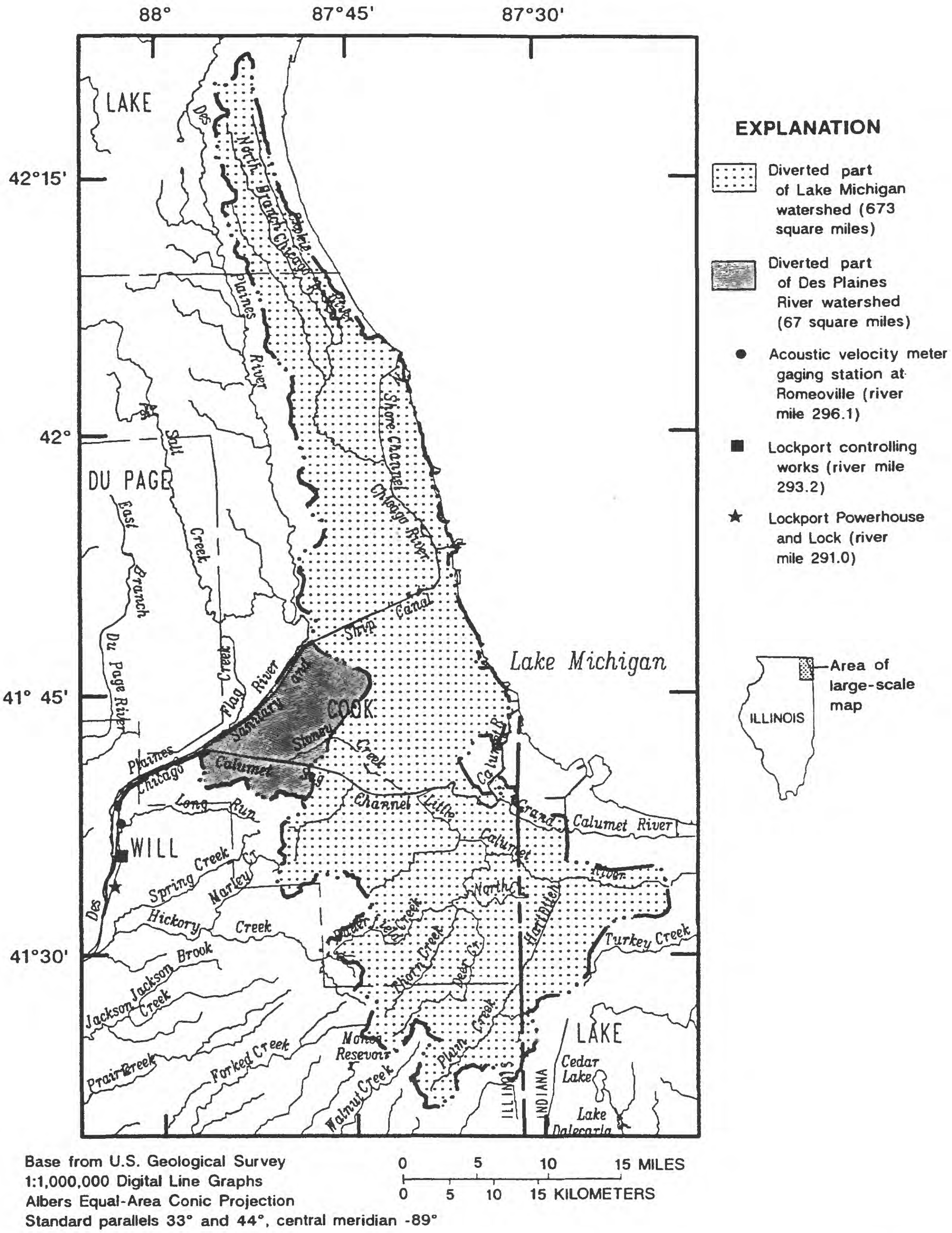

Figure 1.--Chicago Sanitary and Ship Canal and its tributary area and the locations of the acoustic velocity meter at Romeoville, Ill., and the Lockport lock, dam, and controlling works.

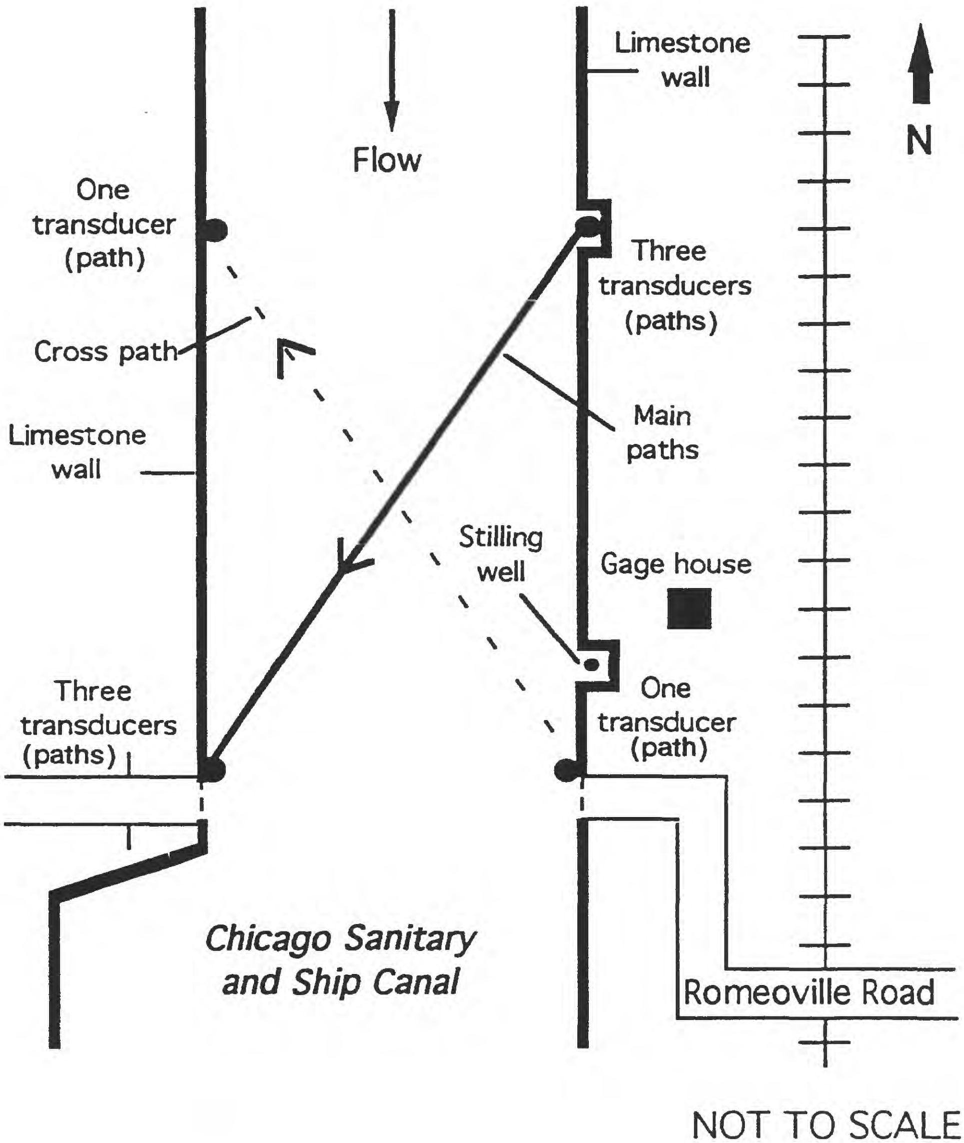

Figure 2.--Locations of the transducers and gage house for the acoustic-velocity-meter installation at Romeoville, Ill.

numerous maintenance problems; on November 17, 1988, it was replaced by an AVM made by ORE, Inc. The installed AVM was and is occasionally rendered inoperative by power surges, damage by barges, and other causes. (See appendix 1 for a summary of periods when the AVM's were inoperative and the causes.) During these periods, discharge estimates made by the Metropolitan Water Reclamation District of Greater Chicago (MWRD) at the Lockport powerhouse, lock, and controlling works, 5.1, 5.1, and 2.9 mi, respectively, downstream from the AVM installation (fig. 1), are used to approximate the flow at Romeoville through a series of regression equations (U.S. Army Corps of Engineers, 1989). The original regression equations were derived from flow data from June 12, 1984, through September 30, 1987, and required updating.

With the convening of the Technical Committee for review of the diversion accounting for water years 1986-90[2], the Corps and USGS have cooperatively developed the most accurate daily mean discharges possible at this time for the Chicago Sanitary and Ship Canal at Romeoville for water years 1986-91. This task included development of a new set of regression equations for the estimation of discharge for periods when the AVM was inoperative. The replacement of the original Sarasota AVM with the ORE AVM in 1988 complicated the task.

Purpose and Scope

This report describes the methods and results of a study to compare, adjust, and revise the daily mean discharge data estimated by the two AVM's on the Chicago Sanitary and Ship Canal at Romeoville during water years 1986-91. The analyses described in this report presently provide the most accurate daily mean discharges possible for the Chicago Sanitary and Ship Canal at Romeoville for the Lake Michigan diversion accounting for water years 1986-91.

Approach

The procedures listed below were followed in the analysis of the AVM discharge data:

1. The discharges computed by the Sarasota AVM and with the use of the ORE AVM were compared by statistical methods and vertical velocity distributions measured by each AVM were compared. Such a comparative analysis ensured that the performance of each AVM was consistent and that the replacement of the Sarasota AVM with the ORE AVM did not introduce a significant bias.

2. The USGS computation programs were used to adjust the discharge estimates for the ORE AVM period of operation using the ORE AVM velocity and stage measurements and the corrected width and depth. The discharge estimates for the Sarasota AVM period of operation were adjusted on the basis of a correction equation applied to the cross-sectional average velocity. A channel cross-section survey was made on June 4 and 5, 1991. The survey

[2]The water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends and which includes 9 of the 12 months.

revealed that the cross section between the AVM transducers that measure velocity is 1.55 ft deeper than had been determined from engineering plans and 2 ft narrower than measured from the Romeoville Road bridge (fig. 2).

3. Equations were developed and verified for estimation of discharges computed by the AVM at Romeoville on the basis of discharges estimated by MWRD at Lockport. These equations followed a format similar to the regression equations by discharge regime developed by the Corps (U.S. Army Corps of Engineers, 1989).

4. The estimation equations were applied to estimate values of daily mean discharge for all periods when the AVM was not operational.

Description of Site

The Chicago Sanitary and Ship Canal, hereafter referred to as "the Canal", was constructed from 1892 to 1900 to reverse the flow of the Chicago River and to carry wastewater from Chicago away from water-supply inlets in Lake Michigan and into the Illinois River Basin. The Canal is 28 mi long, and the last 15 mi are cut into bedrock. In 1910, the 8-mi-long North Shore Channel was constructed and connected to the Canal to carry wastewater from north shore communities and additional water from Lake Michigan for dilution of wastewater. The 18-mi-long Calumet Sag Channel was constructed during 1910-20 to connect the Calumet River to the Canal and to reverse the flow of the Calumet River and carry wastewater from areas south of Chicago to the Illinois River Basin. These channels and the area drained by the Canal are shown in figure 1. The area drained by the Canal at the Romeoville AVM site is 739 mi^2.

The AVM at Romeoville is at river mile 296.1, 5.1 mi upstream from the end of the Canal at the Lockport Lock and Dam (fig. 1). The AVM is in the part of the Canal carved into bedrock. Initially, the transducers were mounted directly into small slots chiseled into the Canal wall. However, the transducers were not adequately protected from damage by barges (see appendix 1). Divers were then required to service the damaged transducers. Therefore, on November 2, 1990, the three main transducers were relocated into large recesses formed in the Canal wall during Canal construction. The transducers were installed into a 6-in. inside-diameter PVC pipe that allowed the transducers to be serviced without the use of divers. Current locations of the transducers and gage house at Romeoville are shown in figure 2. Analysis of the velocity measurements and discharge calculations in water year 1991 showed that the transducer relocation did not introduce a bias in the discharge record.

Acknowledgments

The authors wish to acknowledge the Metropolitan Water Reclamation District of Greater Chicago for assisting in this project by providing discharge estimates for the outlet works at Lockport, for providing a tour of the facilities at Lockport, and for explaining the current methods of estimating discharge through the various outlet works.

COMPARISON AND ANALYSIS OF DISCHARGE DATA

Because of the frequent failures of various components of the Sarasota AVM (see appendix 1) and difficulties in getting it serviced, it was replaced by the ORE AVM. The two systems differ, however, in the way discharge is calculated, the depths of the transducers, and in the internal operation of the meters. These differences raise questions regarding the consistency of the values of daily mean discharge obtained from the two AVM's. The two AVM's were never operated simultaneously. Such operation would be problematic because of interference between acoustic signals from transducers of two AVM's at nearly the same depths. Thus, the consistency of discharge estimates made by the two AVM's can be examined in a generalized statistical manner only.

The discharge calculations that are most directly compatible were used to perform the comparison. The originally calculated ORE AVM discharges for water years 1989 and 1990 did not include adjustments for the width and depth errors detected in 1991; thus, these discharges are considered directly comparable to the Sarasota AVM discharges. In addition, the method used to compute discharge during these years with the ORE AVM was similar to that used by the Sarasota AVM. All discharges were adjusted to correct for the errors in width and depth; however, the adjustment procedure was different for each AVM (as discussed later). Therefore, comparing Sarasota AVM discharges to the ORE AVM discharges for water years 1989 and 1990 is the least biased comparison. The comparison was done in three ways:

1. The actual discharges for the various discharge regimes were compared between the periods of operation for the Sarasota AVM (June 12, 1984, through November 2, 1988) and the ORE AVM (November 18, 1988, through September 30, 1990).

2. The regression equations with MWRD discharge estimates for the various discharge regimes (combinations of outlet works) were compared. In addition, (a) the Sarasota AVM record was estimated with the ORE AVM regressions and (b) the ORE AVM record was estimated with the Sarasota AVM regressions. The residuals, defined as the difference between the AVM discharge and the discharges estimated by the regression relations, for cases (a) and (b) also were compared.

3. The vertical velocity distributions measured by the two AVM's were compared.

If no significant difference between the discharge estimates derived from each AVM can be demonstrated, then the adjustment of the Sarasota AVM and the ORE AVM discharge estimates to account for the width and depth errors can be discussed. The adjustment for the ORE AVM is straightforward, but the adjustment for the Sarasota AVM is complicated because this AVM internally calculated the average 15-minute and daily discharges.

Discharge Estimates Made by the Sarasota and ORE Acoustic Velocity Meters

Table 1 lists the number of days, mean value, variance, standard deviation, and skewness coefficient for each data series; and Student's t for the t-test and the F-statistic for each pair (Sarasota AVM and ORE AVM) of data series. These statistics are given for the following data sets:

1. AVM discharge for all discharge regimes;

2. MWRD discharge for all discharge regimes;

3. AVM discharge minus MWRD discharge for all discharge regimes;

4. AVM discharge for days of turbine, lockage, and leakage (TLL) discharge only;

5. MWRD discharge for days of TLL discharge only;

6. AVM discharge minus MWRD discharge for days of TLL discharge only;

7. AVM discharge for days of turbine, lockage, leakage, and sluice gate (TLL+SG) discharge;

8. MWRD discharge for days of TLL+SG discharge;

9. AVM discharge minus MWRD discharge for days of TLL+SG discharge; and

10. Discharge for Des Plaines River at Riverside.

The discharge-duration curves for discharges measured by the Sarasota AVM and ORE AVM for all discharge regimes, the TLL discharge, and the TLL+SG discharge, are shown in figures 3-5, respectively.

In the skewness test of normality (Salas and others, 1980, p. 93) for data sets of various sizes, if the absolute value of the skewness coefficient is greater than the values given below, the hypothesis that the data series is normally distributed can be rejected at the 2-percent level of significance.

Number of observations	Skewness-coefficient bound
100	0.567
150	.464
500	.255
600	.233
800	.202
1,000	.180

Table 1.--Statistical comparison of 10 data sets for the Sarasota acoustic velocity meter, June 12, 1984, through November 2, 1988, and the ORE acoustic velocity meter, November 18, 1988, through September 30, 1990

[AVM, acoustic velocity meter; MWRD, Metropolitan Water Reclamation District of Greater Chicago; stat., statistic; ft^3/s, cubic feet per second; ft^6/s^2, cubic feet per second squared]

AVM	Number of days operational	Mean (ft^3/s)	Variance (ft^6/s^2)	Standard deviation (ft^3/s)	Skewness coefficient	Z-stat., t-test	F-stat., F-test
Data set 1, AVM discharge (all discharge regimes)							
Sarasota	952	3,696	2,334,168	1,528	3.332	3.59	1.064
ORE	616	3,415	2,193,893	1,481	2.445		
Data set 2, MWRD discharge (all discharge regimes)							
Sarasota	952	3,492	5,682,810	2,384	7.071	1.20	1.184
ORE	616	3,338	6,726,640	2,594	5.010		
Data set 3, AVM discharge minus MWRD discharge (all discharge regimes)							
Sarasota	952	204	1,262,207	1,123	-10.547	2.02	1.440
ORE	616	77	1,818,197	1,348	-6.640		
Data set 4, AVM discharge (turbine, lockage, and leakage)							
Sarasota	792	3,317	729,753	854	.548	5.81	1.226
ORE	497	3,021	894,626	946	1.005		
Data set 5, MWRD discharge (turbine, lockage, and leakage)							
Sarasota	792	2,981	590,238	768	.404	6.95	1.217
ORE	497	2,663	718,166	847	.945		
Data set 6, AVM discharge minus MWRD discharge (turbine, lockage, and leakage)							
Sarasota	792	336	28,554	169	4.537	2.35	1.272
ORE	497	358	22,453	150	.463		
Data set 7, AVM discharge (turbine, lockage, leakage, and sluice gates)							
Sarasota	138	4,930	1,544,442	1,243	.752	3.20	1.231
ORE	100	4,428	1,255,039	1,120	1.289		
Data set 8, MWRD discharge (turbine, lockage, leakage, and sluice gates)							
Sarasota	138	4,715	1,861,043	1,364	1.117	.40	1.947
ORE	100	4,630	3,623,578	1,904	2.786		
Data set 9, AVM discharge minus MWRD discharge (turbine, lockage, leakage, and sluice gates)							
Sarasota	138	215	166,820	408	-2.798	4.40	6.037
ORE	100	-203	1,007,069	1,004	-3.769		
Data set 10, Discharge for Des Plaines River at Riverside							
Sarasota	1,044	713	859,813	927	4.312	2.34	1.950
ORE	682	617	440,991	664	3.408		

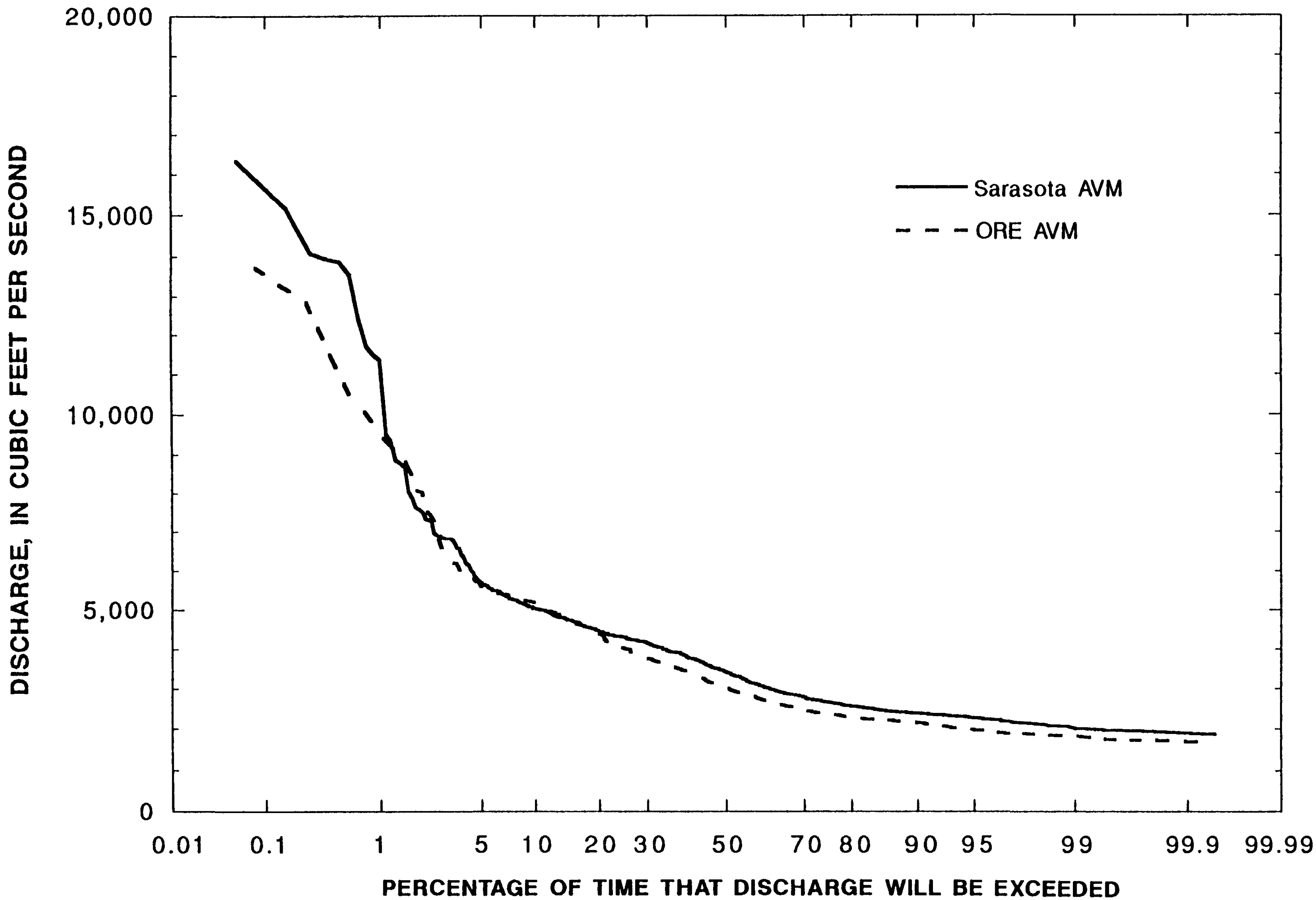

Figure 3.--Discharge-duration curves for unadjusted daily mean discharges measured by Sarasota and ORE acoustic velocity meters for all discharge regimes, Chicago Sanitary and Ship Canal at Romeoville, Ill.

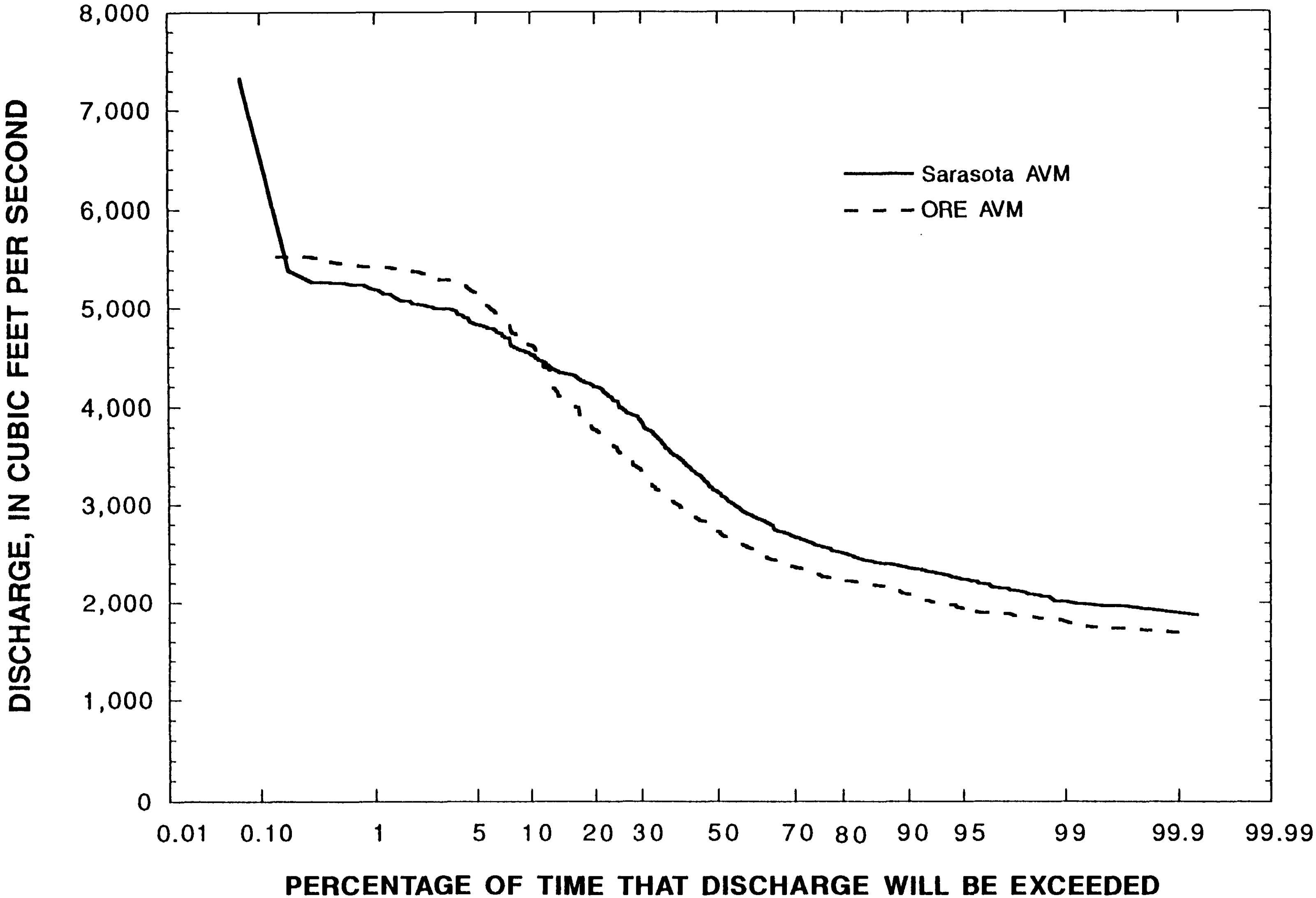

Figure 4.--Discharge-duration curves for unadjusted daily mean discharges measured by Sarasota and ORE acoustic velocity meters for the turbine, lockage, and leakage discharge regime, Chicago Sanitary and Ship Canal at Romeoville, Ill.

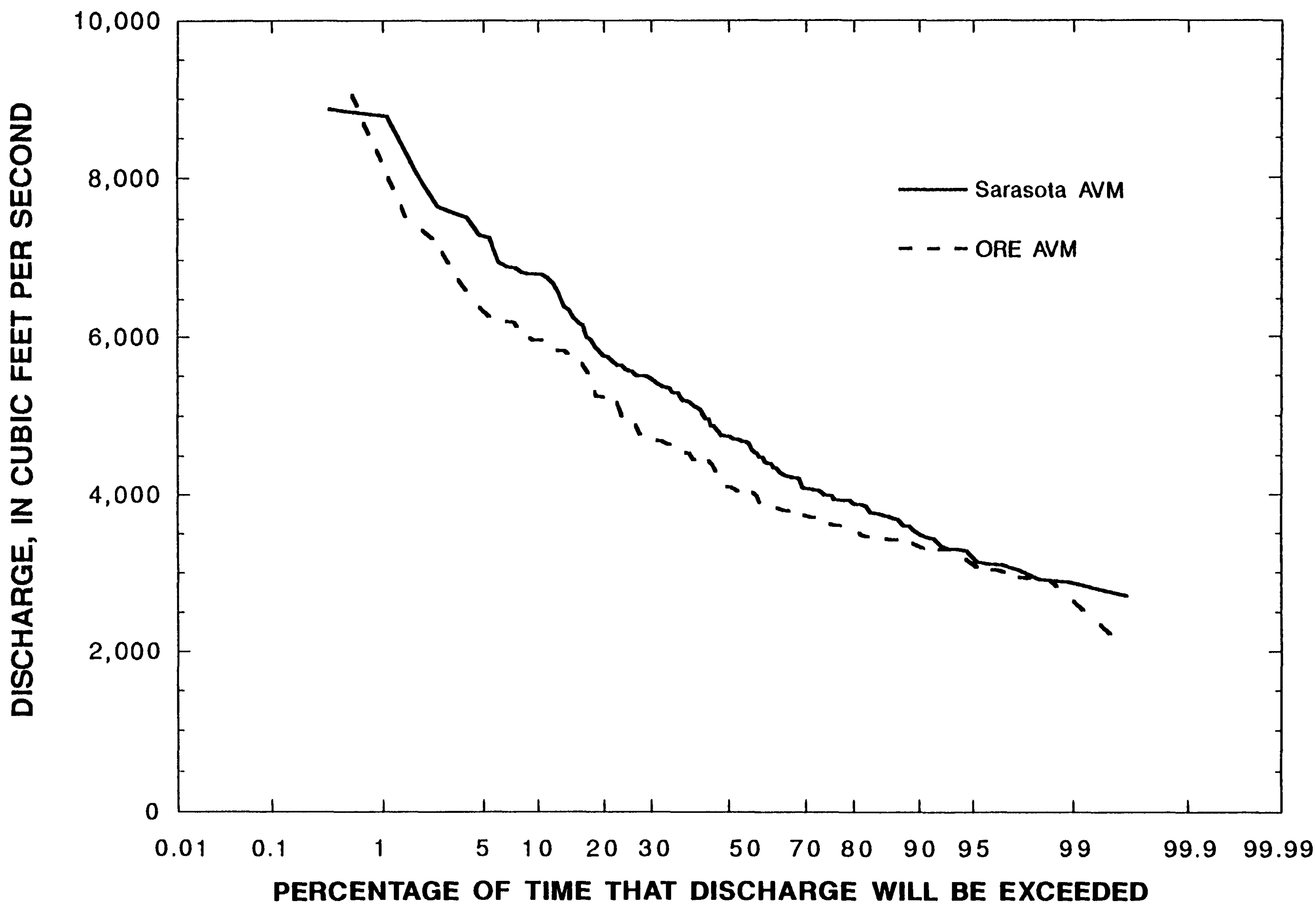

Figure 5.--Discharge-duration curves for unadjusted daily mean discharges measured by Sarasota and ORE acoustic velocity meters for the turbine, lockage, leakage, and sluice-gate discharge regime, Chicago Sanitary and Ship Canal at Romeoville, Ill.

Comparison with the skewness coefficient values in table 1 indicates these data are not normally distributed. Computation of skewness coefficients for the logarithms of the flows failed to reduce the skewness to nonrejection levels for most of the data series. Further, serial correlation between the daily discharges measured by each AVM is high. Thus, the t-test and F-test are not strictly valid for these data series. Nevertheless, the test statistics can still be useful in assessing the magnitude of the differences between the Sarasota AVM and the ORE AVM data-collection periods.

In comparing data series, if both series contained 121 days of discharge (that is, had 120 degrees of freedom), the hypothesis that the variances of the two series are the same could be rejected at the 1-percent significance level if the F-statistic value is greater than 1.53. This threshold becomes smaller as the data sets become larger. Thus, data sets 8, 9, and 10 have significantly different variances. Further, if a data set fails the F-test, the results of the standard t-test used here are invalid because the standard t-test is based on the assumption that the two series have the same variance. It should be noted that an adjusted t-test is available for the case of nonconstant variance; however, because the main question is whether the data are drawn from the same population, such a test is not warranted in this analysis.

If Student's t of the standard t-test is greater than 2.358 or 2.326 for cases of 120 and infinite degrees of freedom, respectively, the hypothesis that the means of the two series are the same can be rejected at the 1-percent significance level. The number of degrees of freedom is equal to the sum of the number of days of discharge in the series being compared minus two. Thus, data sets 1, 4, 5, 6, 7, 9, and 10 have significantly different means.

The only data sets that do not seem to have significantly different statistics for the ORE AVM period relative to the Sarasota AVM period are those for the MWRD discharge estimates and the difference between AVM and MWRD discharge estimates for all discharge regimes. This finding could be considered evidence of an inconsistency in the discharges between the two periods on the part of the MWRD discharge estimates because the two periods were not significantly different, whereas all other discharge data indicate changes between periods; however, because the individual subsets of the discharge data reflecting the different components of the discharge released at Lockport indicate significant differences between the two periods, the overall lack of a significant difference appears to be an artifact of the data. That is, the difference between the AVM and MWRD discharge estimates increases slightly for the ORE AVM period of operation compared to the Sarasota AVM period of operation for days of TLL discharge only, whereas this difference greatly decreases for days when the sluice gates were in operation. These significant increases and decreases cancel one another if the overall discharge data series is considered.

Preliminary analyses by the Corps indicated that discharges computed by the ORE AVM generally were less than those computed by the Sarasota AVM. This conclusion raised the question of whether the Sarasota AVM discharge computations were biased to be higher than those for the ORE AVM. As shown in table 1, the mean value in all the data series in the ORE AVM period of operation are lower than those for the Sarasota AVM period of operation. Thus, the period of ORE AVM operation seems to have been somewhat drier on average than the period of Sarasota AVM operation. Discharges calculated at a nearby streamflow-gaging station, the Des Plaines River at Riverside, show the same trend. The average difference between AVM and MWRD estimates for TLL flow is 127 ft^3/s less in the ORE AVM period than in the Sarasota AVM period, but whether this difference is because of differences between AVM's or entirely because of natural variation cannot be determined.

From table 1, it is clear that distinct differences in flow between the two periods are due to natural variation despite the high degree of regulation of the Canal. This difference is confirmed by the comparisons made by use of discharge data for the Des Plaines River at Riverside, a relatively unregulated river. The natural variations between periods are much greater in magnitude than any difference between discharges computed by the two meters. It seems highly unlikely that statistical methods could be used to prove a difference in data series because of differences in the meters alone, given the problems with serial correlation of daily flows and non-normality of the data.

Regression Relations Between Discharge Estimates at Romeoville and Lockport

As per the recommendations of the Second Technical Committee (Espey and others, 1987) and the procedures followed by the U.S. Army Corps of Engineers (1989), regression relations were derived between AVM values and MWRD values of daily mean discharge for three different discharge regimes. These regression equations follow.

1. TLL discharge only:

$$Q_{AVM} = a_0 + a_1 \times Q_{TLL}, \tag{1}$$

where Q_{AVM} is the AVM discharge,
Q_{TLL} is the MWRD estimate of TLL discharge,
a_0 is the intercept of linear regression line, and
a_1 is the regression coefficient relating Q_{AVM} and Q_{TLL}.

2. TLL+SG discharge:

$$Q_{AVM} = a_0 + a_1 \times Q_{TLL} + a_2 \times Q_{SG}, \tag{2}$$

where Q_{SG} is the MWRD estimate of sluice-gate (SG) discharge, and
a_2 is the regression coefficient relating Q_{AVM} and Q_{SG}.

3. Turbine, lockage, leakage, sluice-gate, and controlling-works (TLL+SG+CW) discharge:

$$Q_{AVM} = a_0 + a_1 \times Q_{TLL} + a_2 \times Q_{SG} + a_3 \times Q_{CW}, \tag{3}$$

where Q_{CW} is the MWRD estimate of the controlling-works (CW) discharge, and
a_3 is the regression coefficient relating Q_{AVM} and Q_{CW}.

The values of a_0, a_1, and a_2 are different for each of equations 1-3.

To test the consistency of the Sarasota AVM and the ORE AVM discharges, equations 1-3 were fit to data for the Sarasota AVM and the ORE AVM from water years 1989 and 1990. The STATIT statistical package (Statware, Inc., 1990) was used for the regression analysis. Regression coefficients a_0-a_3 and their standard errors for each of the discharge regimes and time periods (Sarasota AVM and ORE AVM) are listed in table 2. The closeness of fit between the regression equation and the data is measured by the coefficient of determination (R^2), standard error of regression (S_e), and standard error as a fraction of mean discharge (Q_M) for the given discharge regime (S_e/Q_M), which are listed in table 3.

Table 2.--Regression coefficients and standard errors of the multiple linear regression of acoustic-velocity-meter discharges at Romeoville, Ill., approximated on the basis of discharge estimates made by the Metropolitan Water Reclamation District of Greater Chicago for Lockport, Ill., for the various discharge regimes (combinations of outlet works); separate equations are provided for the periods of operation for the Sarasota and ORE acoustic velocity meters

[AVM, acoustic velocity meter; a_0, intercept of the multiple linear regression; a_1, regression coefficient between the AVM discharge and the Metropolitan Water Reclamation District of Greater Chicago (MWRD) estimate of turbine, lockage, and leakage discharge for the given data set; a_2, regression coefficient between the AVM discharge and the MWRD estimate of sluice-gate discharge for the given data set; a_3, regression coefficient between the AVM discharge and the MWRD estimate of controlling-works discharge; all coefficients are used to estimate daily mean discharge in cubic feet per second; --, no value calculated]

Discharge regime	Regression coefficient	Sarasota AVM[1] Coefficient value	Sarasota AVM[1] Standard error	ORE AVM[2] Coefficient value	ORE AVM[2] Standard error
Turbine, lockage, and leakage	a_0	55.88	21.78	72.33	17.66
	a_1	1.094	.0071	1.107	.0063
Sluice gates	a_0	100.5	96.16	804.1	101.3
	a_1	1.136	.0262	.976	.0319
	a_2	.736	.0190	.411	.0158
Controlling works	a_0	1,332	848.6	4,127	354.2
	a_1	.9943	.2318	--	--
	a_2	.6647	.0340	.3384	.0373
	a_3	--	--	.5121	.0703

[1]Period of operation considered, June 12, 1984, through November 2, 1988.
[2]Period of operation considered, November 18, 1988, through September 30, 1990.

For the equations involving CW discharges, blank values for a coefficient indicate that the value of the regression coefficient was not significantly different from zero. In this analysis the multiple linear regression is repeated, but the weakly correlated independent variable is omitted to produce a closer fit. For the Sarasota AVM period, an a_3 value of -0.0425 with a standard error of 0.159 was calculated for the multiple regression including a_3. For the Sarasota AVM period, the CW discharges generally were much less than the SG discharges for 20 of 22 days when the CW was in operation. For these 20 days, the CW discharges were, on average, equal to 36 percent of the SG discharges, with 5 days less than 10 percent. On days when discharges were

Table 3.--Closeness of fit of the regression equation for the various discharge regimes for the Sarasota acoustic velocity meter, June 12, 1984, through November 2, 1988, and the ORE acoustic velocity meter, November 18, 1988, through September 30, 1990

[AVM, acoustic velocity meter; R^2, coefficient of determination for the regression equation; S_e, standard error of the regression equation; Q_M, mean discharge for the given discharge regime; ft^3/s, cubic feet per second]

AVM	Discharge regime	R^2	S_e (ft^3/s)	S_e/Q_M (percent)
Sarasota	Turbine, lockage, and leakage	0.968	153.0	4.61
ORE	Turbine, lockage, and leakage	.984	119.4	3.95
Sarasota	Turbine, lockage, leakage, and sluice gates	.959	251.7	5.11
ORE	Turbine, lockage, leakage, and sluice gates	.947	258.3	5.83
Sarasota	Turbine, lockage, leakage, sluice gates, and controlling works	.947	928.7	9.69
ORE	Turbine, lockage, leakage, sluice gates, and controlling works	.916	768.8	9.14

lower, the CW discharges were negligible; on the days when discharges were high, the CW discharges were strongly correlated to the SG discharges. The combination of the two were much greater than the AVM discharges. Thus, the CW contributed little to the estimation of AVM discharges. Similar results were found by the Corps (U.S. Army Corps of Engineers, 1989). For the ORE AVM period, an a_1 value of 0.222 with a standard error of 0.268 was calculated for the multiple linear regression including a_1. The TLL influence on the total discharge is implicitly included in the regression equation in the intercept, a_0, value of 4,127. The average TLL discharge during days with CW discharge for the ORE AVM period is 3,159 ft^3/s. Subtracting this value from a_0 yields 968, which is similar to the a_0 value for the Sarasota AVM period and to the a_0 value for days of SG discharge. The average value of TLL discharge is important because of an operational difference between the water years. For the first 10 days of water year 1989 on which the CW was operational, the TLL discharge ranged from 2,000 to 2,600 ft^3/s, whereas on the last day of CW operation in water year 1989 and during the 8 days of CW operation in water year 1990, the TLL discharge ranged from 3,500 to 4,500 ft^3/s. Therefore, a regression equation calculated from the individual values of TLL discharge produced a poor fit, whereas a regression equation implicitly incorporating the average value of TLL discharge resulted in a closer fit.

The regression relations for the TLL discharge regime are nearly identical for the Sarasota AVM and the ORE AVM periods. Practically, the difference in intercepts is only 16.45 ft^3/s, which is only 0.5 percent of the average TLL discharge for the two periods, and the difference in slope is only 1.2 percent. Statistically, the difference in coefficient values for each regression equation is small relative to the standard errors of the coefficient values.

The difference in the regression equations for the other discharge regimes is statistically significant; however, this is primarily because of the large errors in the MWRD estimates of SG and CW discharge, which have been discussed in detail by the First and Second Technical Committees (Espey and others, 1981; 1987). An example of the high uncertainty in defining a relation between AVM discharges at Romeoville and the MWRD discharge estimates at Lockport, when the sluice gates are operating, is the Corps regression (U.S. Army Corps of Engineers, 1989) of data through September 30, 1987, which produced an a_2 value of 0.796. Thus, by adding another year of data (an additional 28 data points), the regression relation changed by more than three standard-error values. As discussed previously, the difference in the regression equations for days of CW operation is partly because of the implicit inclusion of the average TLL discharge in the intercept of the ORE AVM equation. Subtracting this average value indicates that the intercepts of the equations for the two periods are similar.

In a further comparison of the regression equations between the two periods, the ORE AVM regression equations were used to estimate discharges for the Sarasota AVM period. The Sarasota AVM regression equations, in turn, were used to estimate discharges for the ORE AVM period. Two sets of computations were made for each comparison--one for the TLL discharge only and one for all discharge regimes.

The mean, standard deviation, and skewness coefficient of the residuals (measured value minus estimated value) for the ORE AVM period, TLL discharge only, were 55.69 ft^3/s, 119.7 ft^3/s, and -0.0835, respectively. The mean, standard deviation, and skewness coefficient of the residuals for the Sarasota AVM period, TLL discharge only, were -55.90 ft^3/s, 153.1 ft^3/s, and 4.769, respectively. The hypothesis that the regression equations are equivalent for practical purposes is further supported by the near equality of the standard deviations of the residuals and the standard errors of the regression equations for the appropriate periods. The mean values of the residuals seem to indicate that the ORE AVM estimates tend to be about 50 ft^3/s higher than the Sarasota AVM estimates. The product of the difference in slopes (a_1) and the average TLL discharge for the entire period (3,202 ft^3/s) is 42.3 ft^3/s. Thus, the 50-ft^3/s difference is mainly because of the difference in slopes of the linear regression line. Further, because the slopes are not significantly different, it can be concluded that differences between the discharge computations made by the two AVM's cannot be documented.

The mean, standard deviation, and skewness coefficient of the residuals for the ORE AVM period for all discharge regimes were 165.8 ft^3/s, 421.4 ft^3/s, and -5.480, respectively. The mean, standard deviation, and skewness coefficient of the residuals for the Sarasota AVM period for all discharge regimes were 18.29 ft^3/s, 396.6 ft^3/s, and 5.358, respectively.

The regression equations derived for the periods of operation of the Sarasota AVM and the ORE AVM were further compared by considering the absolute difference between the discharge values estimated by each set of regression equations divided by the AVM discharge estimate on that day. The absolute relative difference, ARD, is defined as

$$ARD = |Q_{SAR} - Q_{ORE}| / Q_{AVM}, \quad (4)$$

where Q_{SAR} is the discharge estimated by the regression equations developed for the period of Sarasota AVM operation and Q_{ORE} is the discharge estimated by the regression equations developed for the period of ORE AVM operation. For the period of Sarasota AVM operation, the mean and standard deviation of the ARD are 1.39 and 0.66 percent, respectively, for days of TLL discharge only and 2.71 and 4.23 percent, respectively, for all days. For the period of ORE AVM operation, the mean and standard deviation of the ARD are 1.35 and 0.68 percent, respectively, for days of TLL discharge only and 2.89 and 4.66 percent, respectively, for all days. From this comparison, it is clear that the difference between use of either set of equations to predict either period is, on average, less than 3 percent. This small difference supports the practical equivalence of the two sets of regression equations.

On the basis of the practical and statistical consideration of the regression equations and the testing of the regression equations for each AVM against the measurements made by the other AVM, no significant differences between the two AVM's can be detected. Further, from a practical point of view, the differences in the estimates from the two sets of regression equations are less than 5 percent of the total flow, which is approximately the accuracy of the AVM equipment.

Vertical Velocity Distributions

Path-ratio velocity analyses were done for ORE AVM data (39,528 sets of four-path velocity measurements made from July 1991 through September 1992) and for Sarasota AVM data (12,353 sets of four-path velocity measurements made from March through October 1987). In these analyses, ratios were determined between the velocity of a given path and the cross-sectional average velocity. Because of the relocation of the transducers of the AVM equipment at the site between 1988 and 1991, these ratios are not directly comparable. The mean and 1 standard deviation confidence limits of the ratio of path velocity to cross-sectional average velocity are shown as a function of transducer elevation in figure 6. This linear plot shows consistency between the vertical velocity-distribution measurements made by the Sarasota AVM and the ORE AVM.

The middle path estimates the average velocity of the flow at a given elevation by measuring the traveltime of acoustic signals moving with the flow, whereas the cross path estimates the average velocity of the flow at a given elevation by measuring the traveltime of acoustic signals moving in opposition to the flow. The difference between the velocities measured by these two paths at nearly the same elevation indicates the angularity of the flow. In a preliminary analysis of 576 sets of four-path velocity data from July 1991, which yielded nearly identical ratios to those for the entire ORE data set, D.A. Stedfast (U.S. Geological Survey, written commun., 1991) concluded that the difference between the middle-path and cross-path velocities was sufficiently small that it could easily be because of equipment precision errors and (or) errors in the measurement of the path angles and length. Thus, he concluded that there is no significant difference between the path velocities. Similar conclusions can be drawn for the 1988 analysis of Sarasota data.

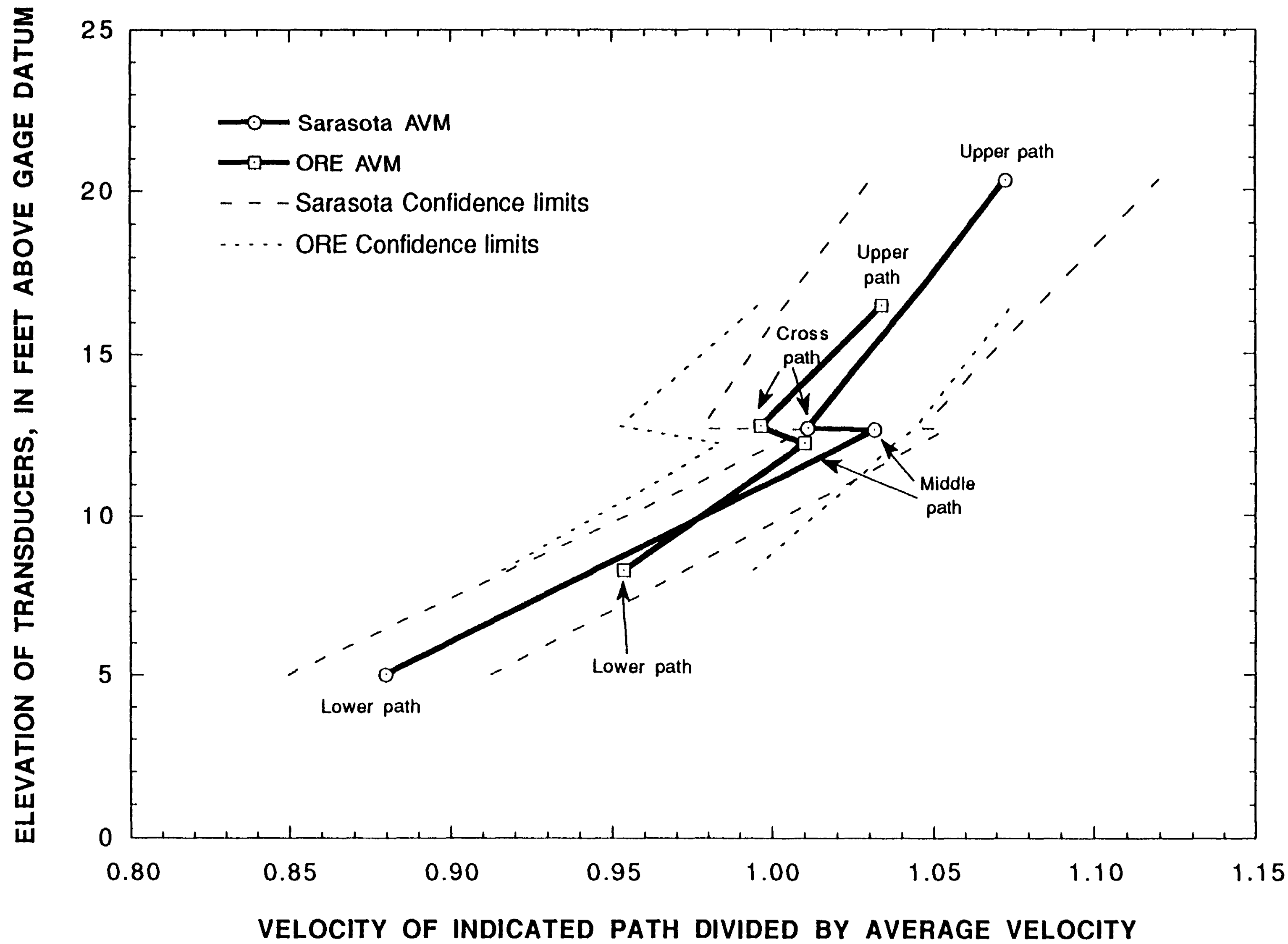

Figure 6.--Nondimensional vertical velocity distribution and 1 standard-deviation confidence limits (bounds) based on measurements by the Sarasota and ORE acoustic velocity meters.

Figure 7 shows the results of deleting the cross-path velocity and fitting a simple equation of the form

$$u(y)/\bar{u} = ay^{1/n}, \tag{5}$$

where u(y) is velocity at depth y,
$\bar{u}$ is cross-sectional average flow velocity,
a is a constant coefficient, and
n is a constant exponent.

The cross-path velocity was deleted because it includes some effects of flow angularity, and these effects, although small, could bias the fitting of equation 5. Equation 5 has a power-law form for the velocity distribution similar to that first proposed by Prandtl in 1925 for flow in pipes (see Prandtl and Tietjens, 1934, p. 70-72). Several power-law formulations of various levels of complexity have been proposed for open-channel flow (Keulegan, 1938; Yen, 1992). Equation 5 is a formulation of the type that Chiu (1991) refers to as one of the most widely used in open-channel flow. The two curves in figure 7 are in close agreement. The values of n are 6.84 and 8.42 for the Sarasota AVM and the ORE AVM curves, respectively. These n values are in the general range reported for open-channel flows.

The agreement in vertical-velocity distributions between the two AVM's is only relative to the cross-sectional average velocity. No conclusions can be made regarding the velocity-magnitude measurements made by the two AVM's.

Correction of Discharge for Channel-Width and Depth Errors

On the basis of preliminary measurements made by the Rock Island District of the Corps, the Second Technical Committee (Espey and others, 1987) suggested that the Canal could be deeper than had been determined from the original design of the Canal. On June 4 and 5, 1991, the channel cross sections were measured at three points: (1) the upstream transducers, (2) the downstream transducers, and (3) a point midway between the transducers. The channel was found to be somewhat deeper than indicated by the original engineering plans and 2 ft narrower than had been estimated from measurements at the Romeoville Road bridge (now closed) just downstream from the gage. The measured bottom elevations relative to the original gage datum are given in table 4 and figure 8. The average bottom elevations at each location (determined by trapezoidal integration) and the average bottom elevation for the reach also are given. The average bottom elevation for the reach was computed by trapezoidal integration of the upstream, middle, and downstream elevations. From the corrected average bottom elevation and width, the flow area, A, in square feet, can be computed as

$$A = 162 \times (GH + 1.55), \tag{6}$$

where GH is gage height, in feet, above the original gage datum. The flow area was previously computed as

$$A = 164 \times GH. \tag{7}$$

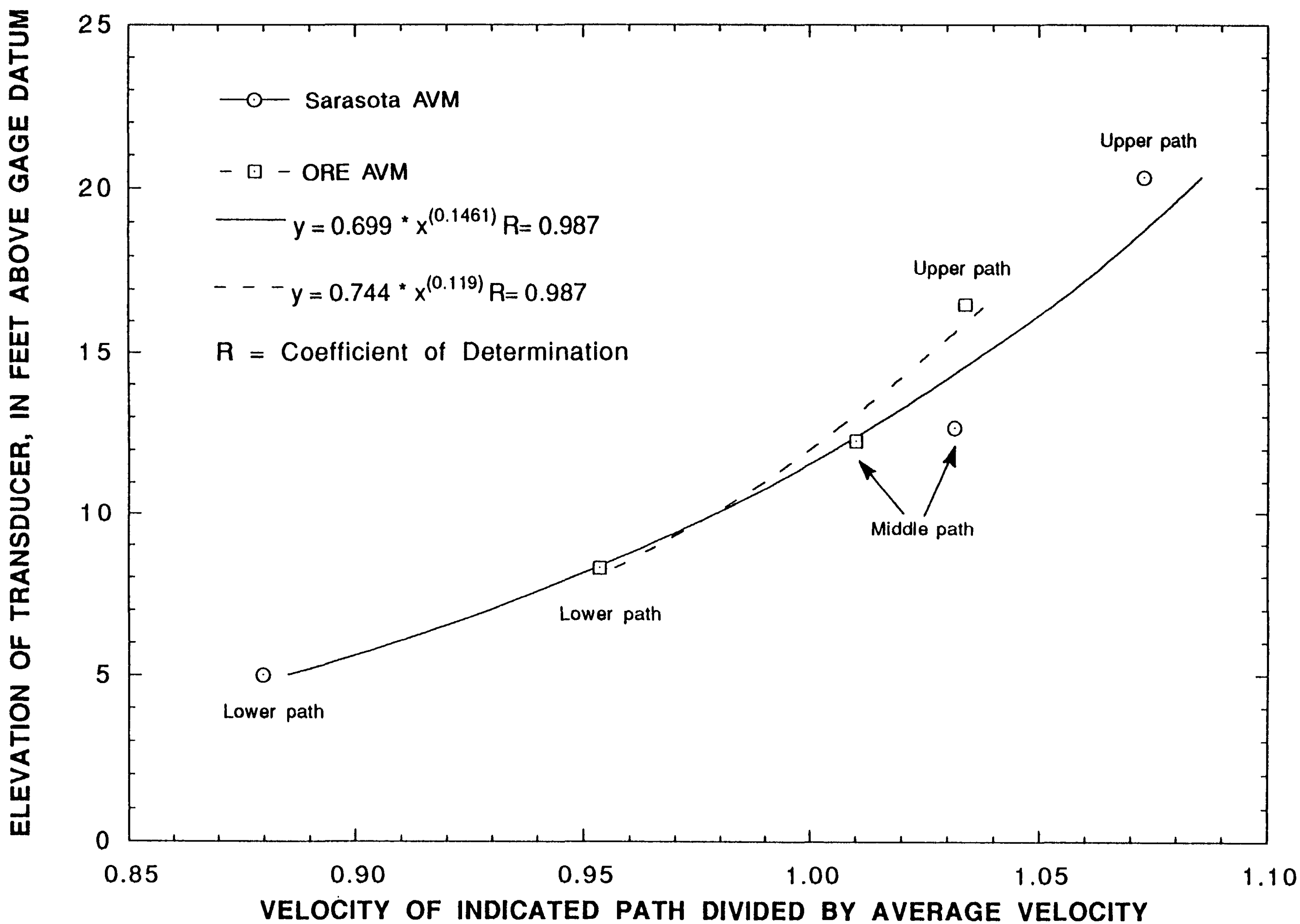

Figure 7.--Nondimensional vertical velocity distribution of the main paths measured by the Sarasota and ORE acoustic velocity meters and the best-fit power-equation representation of the data.

Table 4.--Calculated bottom-elevation data for the Chicago Sanitary and Ship Canal elevations measured at Romeoville, Ill., June 4 and 5, 1991

[Station, position of measurement point relative to a fixed point on the bank of the canal; elevation, elevation of the canal bottom relative to the original gage datum at the given station; average elevation, average elevation relative to the original gage datum between the current and previous stations; area, product of the average elevation and the distance between the current and previous stations; width, canal width at the given location; ft, feet; ft^2, square feet; --, not applicable]

Upstream transducer				Point midway between transducers				Downstream transducer			
Station (ft)	Elevation (ft)	Average elevation (ft)	Area (ft^2)	Station (ft)	Elevation (ft)	Average elevation (ft)	Area (ft^2)	Station (ft)	Elevation (ft)	Average elevation (ft)	Area (ft^2)
6	30	--	--	6	30	--	--	6	30	--	--
6	1.5	--	--	6	-2.4	--	--	6	3.7	--	--
8	.9	1.2	2.4	10	-1.9	-2.15	-8.6	9	6.6	5.15	15.45
10	.3	.6	1.2	14	-2.2	-2.05	-8.2	11	6.6	6.6	13.2
14	.3	.3	1.2	18	-1.5	-1.85	-7.4	15	3.1	4.85	19.4
18	.5	.4	1.6	22	-1.3	-1.4	-5.6	19	1.4	2.25	9.0
22	.7	.6	2.4	26	-1.6	-1.45	-5.8	23	1.5	1.45	5.8
26	.3	.5	2.0	30	-1.8	-1.7	-6.8	27	.2	.85	3.4
30	-.3	0	0	34	-2.0	-1.9	-7.6	31	.5	.35	1.4
34	-1.3	-.8	-3.2	38	-2.4	-2.2	-8.8	35	-.7	-.1	-.4
38	-1.7	-1.5	-6.0	42	-3.0	-2.7	-10.8	39	-.8	-.75	-3.0
42	-1.8	-1.75	-7.0	46	-3.1	-3.05	-12.2	43	-1.2	-1.0	-4.0
46	-2.0	-1.9	-7.6	50	-1.9	-2.5	-10.0	47	-1.1	-1.15	-4.6
50	-2.0	-2.0	-8.0	54	-3.0	-2.45	-9.8	51	-1.5	-1.3	-5.2
54	-2.0	-2.0	-8.0	58	-3.0	-3.0	-12.0	55	-1.4	-1.45	-5.8
58	-1.6	-1.8	-7.2	62	-2.7	-2.85	-11.4	59	-1.5	-1.45	-5.8
62	-1.8	-1.7	-6.8	66	-2.9	-2.8	-11.2	63	-1.3	-1.4	-5.6
66	-2.1	-1.95	-7.8	70	-2.7	-2.8	-11.2	67	-1.4	-1.35	-5.4
70	-2.1	-2.1	-8.4	74	-2.8	-2.75	-11.0	71	-1.2	-1.3	-5.2
74	-1.9	-2.0	-8.0	78	-3.0	-2.9	-11.6	75	-1.6	-1.4	-5.6
78	-2.0	-1.95	-7.8	82	-2.8	-2.9	-11.6	79	-1.6	-1.6	-6.4
82	-2.0	-2.0	-8.0	86	-3.0	-2.9	-11.6	83	-1.4	-1.5	-6.0
86	-2.0	-2.0	-8.0	90	-2.6	-2.8	-11.2	87	-1.7	-1.55	-6.2
90	-1.8	-1.9	-7.6	94	-2.4	-2.5	-10.0	91	-1.8	-1.75	-7.0
94	-1.8	-1.8	-7.2	98	-2.5	-2.45	-9.8	95	-.9	-1.35	-5.4
98	-1.9	-1.85	-7.4	102	-2.4	-2.45	-9.8	99	-1.3	-1.1	-4.4
102	-2.2	-2.05	-8.2	106	-2.1	-2.25	-9.0	103	-1.5	-1.4	-5.6
106	-2.3	-2.25	-9.0	110	-2.2	-2.15	-8.6	107	-1.2	-1.35	-5.4
110	-2.1	-2.2	-8.8	114	-2.1	-2.15	-8.6	111	-1.3	-1.25	-5.0
114	-2.3	-2.2	-8.8	118	-1.8	-1.95	-7.8	115	-1.7	-1.5	-6.0
118	-2.4	-2.35	-9.4	122	-2.0	-1.9	-7.6	119	-1.7	-1.7	-6.8
122	-1.9	-2.15	-8.6	126	-1.9	-1.95	-7.8	123	-1.8	-1.75	-7.0
126	-2.5	-2.2	-8.8	130	-1.8	-1.85	-7.4	127	-1.8	-1.8	-7.2
130	-2.6	-2.55	-10.2	134	-1.7	-1.75	-7.0	131	-1.5	-1.65	-6.6
134	-2.6	-2.6	-10.4	138	-1.6	-1.65	-6.6	135	-1.8	-1.65	-6.6
138	-2.2	-2.4	-9.6	142	-1.7	-1.65	-6.6	139	-1.2	-1.5	-6.0
142	-2.1	-2.15	-8.6	146	-1.4	-1.55	-6.2	143	-1.2	-1.2	-4.8
146	-1.9	-2.0	-8.0	150	-1.2	-1.3	-5.2	147	-.9	-1.05	-4.2
150	-1.7	-1.8	-7.2	154	-.5	-.85	-3.4	151	-.3	-.6	-2.4
154	-1.7	-1.7	-6.8	158	-.9	-.7	-2.8	155	.4	.05	.2
158	-1.9	-1.8	-7.2	162	-1.0	-.95	-3.8	159	1.1	.75	3.0
162	-1.8	-1.85	-7.4	164	-1.1	-1.05	-2.1	163	2.2	1.65	6.6
166	-1.8	-1.8	-7.2	168	-.7	-.9	-3.6	168	4.0	3.1	15.5
168.5	-1.4	-1.6	-4.0	168	30			168	30		
168.5	30										
Total area = -261.4 ft^2				Total area = -338.1 ft^2				Total area = -66.65 ft^2			
Width = 162.5 ft				Width = 162 ft				Width = 162 ft			
Mean elevation = -1.609 ft				Mean elevation = -2.087 ft				Mean elevation = -0.411 ft			

Average elevation for the three cross sections = (-1.609 + 2(-2.087) -0.411)/4 = -1.549

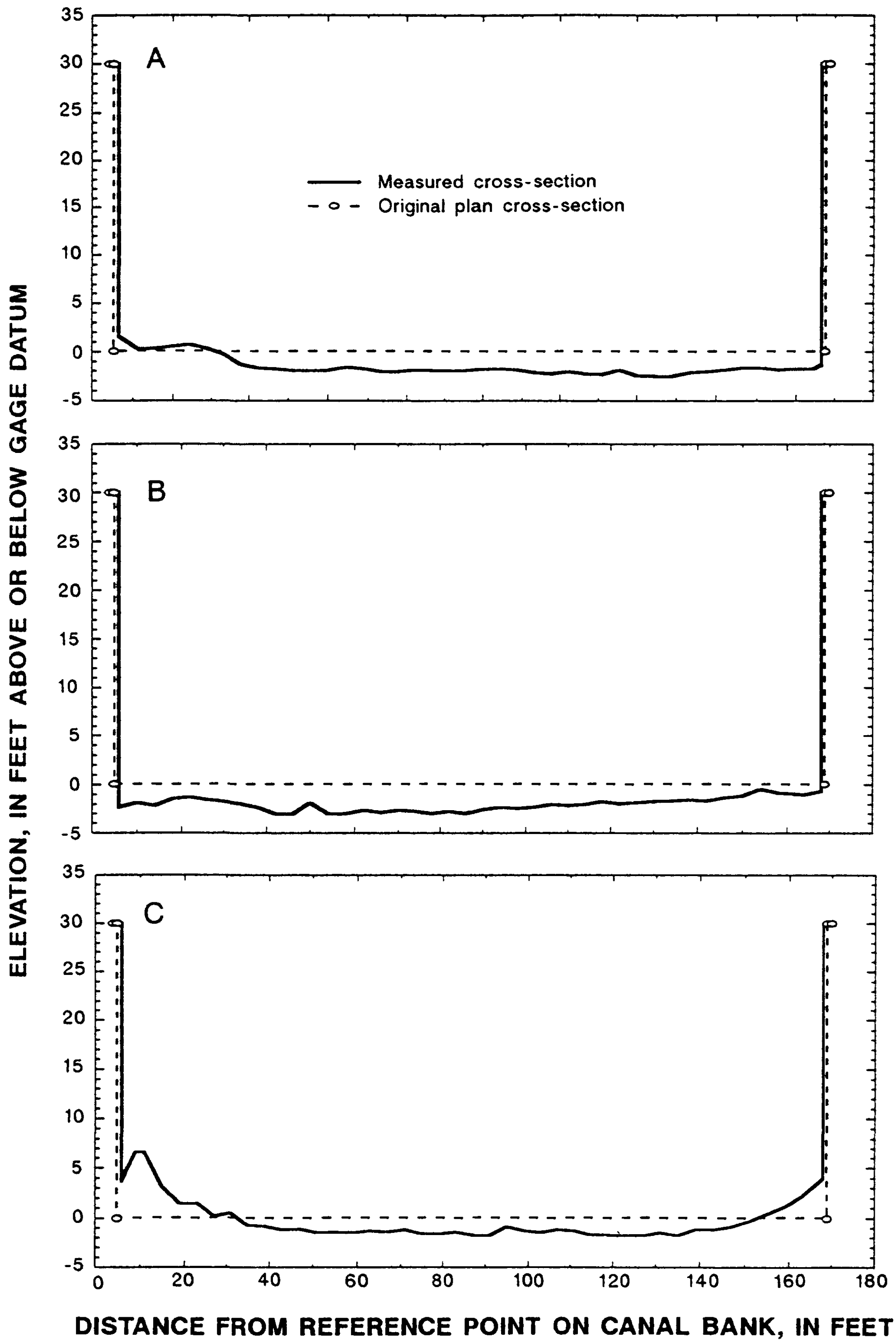

Figure 8.--Cross sections measured on June 4 and 5, 1991, at (A) the upstream transducers, (B) midway between the transducers, and (C) the downstream transducers for the acoustic velocity meter on the Chicago Sanitary and Ship Canal at Romeoville, Ill.

Two methods were used to compute discharges for the ORE AVM from the stage and velocities measured by the AVM. For water years 1989 and 1990, discharge was computed in horizontal slices of the cross section corresponding to each of the four velocity paths of the AVM (if a path is not functioning, the extent of the slices is adjusted). Discharge was computed by summing each of the horizontal slices. For water year 1991 to present (March 1993), discharge was computed by use of the index-velocity method (Rantz and others, 1982, p. 429-470). In this method, the average velocity of all functional paths (the index velocity) is first computed. The index velocity is then adjusted to the cross-sectional average velocity by a curve derived from USGS flow measurements. These two methods were used to recompute the discharges for the ORE AVM by reexecuting the computer programs developed by the USGS incorporating the gage height and area corrections indicated in equation 6.

Sarasota AVM discharges were not as easily corrected. The Sarasota AVM internally calculated the discharge from measured velocities, gage height, and several correction coefficients. The values of these correction coefficients represented a meter calibration. The coefficients were set by the manufacturer and were never provided to the USGS. These calculations were done at short time intervals, and 15-minute average values of the discharge, velocities for functioning paths, gage height, and daily mean discharge were printed and stored in a cassette-tape recorder. Data were stored on cassette tapes beginning in November 1986. Because the details of the internal calculations and the short time intervals are not known, the following approach was used to correct the daily mean discharge.

During water years 1987 and 1988, the daily mean discharges had been adjusted to account for a gage-height correction of 0.24 ft. This correction was determined by computing the difference between simultaneous gage-height readings from the wire-weight gage on the Romeoville Road bridge (fig. 1) and the AVM stage transducer. Originally, the correction was made by increasing the daily mean discharges by 1.2 percent; that is, by multiplying the daily mean discharge by 1.012. Instead of this method of adjustment, the gage-height correction of 0.24 ft was included directly in the area correction. Thus, the corrected gage height used to recalculate the daily mean discharges for water years 1987 and 1988 was 1.79 ft.

The Sarasota AVM computed discharge by means of the approach of horizontal slices of the cross section, as was done with the ORE AVM in water years 1989 and 1990. In the horizontal-slice method of discharge computation used with the ORE AVM, the discharge below the lowest transducer is calculated as

$$Q = V_b\ B\ (h/2) + 0.8V_b\ B\ (h/2), \qquad (8)$$

where V_b is the velocity measured at the lowest functioning transducer,
B is the canal width, and
h is the depth from the lowest functioning transducer to the canal bottom.

The first term in equation 8 represents the area between the lowest transducer and halfway to the bottom, and the second term represents the area between the bottom of the Canal and the lowest functioning transducer. The increase in depth detected by the June 1991 survey is thus subject to an average velocity of 0.9 V_b. Application of this same procedure to the correction of Sarasota AVM discharge measurements results in

$$Q_{adj} = Q_{old} + 162 \times 1.79 \times 0.9 \times V_b = Q_{old} + 261 \times V_b, \quad (9)$$

where Q_{adj} is the adjusted discharge in cubic feet per second and
Q_{old} is the original discharge in cubic feet per second.

Further, comparisons of the velocity measured at the lowest transducer with the corresponding cross-sectional average velocity, V_m, of 12,353 measurements when all four velocity paths were operational show that the velocity measurement made by the lowest transducer was equal to $0.88V_m$ on average. Thus, the adjusted discharge for the Sarasota AVM was obtained from

$$Q_{adj} = Q_{old} + 229.7 \times V_m. \quad (10)$$

The use of $0.8V_b$ for the lowest depths is proper for the ORE AVM; however, for the Sarasota AVM, the lowest transducer is 5.26 ft lower than that for the ORE AVM (in water years 1989 and 1990 when the horizontal-slice method was used; in 1991, the lowest path was lowered to the position shown in figs. 6 and 7). Thus, a value less than $0.8V_b$ is more appropriate for the Sarasota AVM, but this value was used internally by the Sarasota AVM and is not known. Further, it would be more proper to multiply the gage-height correction of 0.24 ft by the velocity measured at the top transducer. The underestimation of the increase in discharge because of the gage-height correction probably is compensated for by the overestimation of discharge in the bottom parts of the channel. Although this calculation is somewhat crude, it is likely that the overall error is no more than 1 percent of the long-term average flow.

The cross-sectional average velocity to be used with equation 10 is then determined by one of the following methods:

1. For days for which complete 15-minute data were stored on cassette tapes and could be restored to the computer, the 15-minute average discharge was divided by the old flow area from equation 7 to determine a 15-minute average velocity. This 15-minute average velocity was then used in equation 10 to determine the adjusted discharge. These adjusted 15-minute average discharges were then averaged for the day to determine the adjusted daily mean discharge. The average of the unadjusted 15-minute average discharge did not equal the unadjusted daily mean discharge because of the differences in the averaging process; however, the differences usually are less than 1 percent and are unbiased. Therefore, it is unlikely that this error in the computation of the daily mean discharge will significantly affect the estimation of long-term average discharges at Romeoville.

2. Unfortunately, for 128 days in water years 1987 and 1988, the information stored on cassette tapes could not be recovered, and the printer output had to be used. Attempts to electronically scan the printer output directly into a machine-readable form were unsuccessful, primarily because optical character-recognition software could not reliably interpret the printout. Therefore, it was decided to calculate a daily mean gage height and then divide the original daily mean discharge by the unadjusted daily mean area

from equation 7 to determine the daily mean velocity. This daily mean velocity was then used in equation 8 to determine the adjusted daily mean discharge. Results from this approach were compared with the daily mean of the adjusted 15-minute discharges for a 300-day period of restored data, and it was found to have a median error (50 percent of errors smaller and 50 percent larger than this value) of 0.26 ft^3/s and an average error of 1.92 ft^3/s. Therefore, the difference in procedures is unlikely to seriously affect the estimation of long-term average discharges at Romeoville.

REGRESSION EQUATIONS FOR ESTIMATION OF MISSING DATA

A technique was needed for estimating daily mean discharge for days on which the AVM was either inoperative or not functioning properly (appendix 1). The technique devised for estimating missing AVM record is based on a set of equations that relate AVM-computed discharges at Romeoville to MWRD discharge estimates at the powerhouse, lock, and controlling works at Lockport. Development of this set of equations required answers to two questions: What data should be used to develop these equations, and what is the proper form of these equations?

Before discussing these questions, the goal of developing statistical-estimation equations must be defined. As described by Larimore and Mehra (1985), this goal is

> "...to obtain a model of the predictable behavior of the process but to avoid incorporating the random characteristics of the particular data set...Beyond a certain complexity, the model ends up fitting the noise in the data trying to explain every wiggle in the data."

Therefore, equations are sought that are effective estimators but not necessarily the best fit to a given set of data.

Data Used to Develop Equations

As discussed previously, there are no demonstrable, significant differences in the performance of the Sarasota AVM compared to the ORE AVM; however, the procedure for adjusting the discharge measurements made by the two AVM's is different and, in the case of the Sarasota AVM, involves certain assumptions. Therefore, the use of separate sets of equations for estimation of missing AVM record for the period of Sarasota AVM operation (October 1, 1985, through November 2, 1988) and the period of ORE AVM operation (November 18, 1988, through September 30, 1991) was examined. The advantage of combining the two data sets is that a broader range of flows at the AVM site at Romeoville and at Lockport is considered in the complete data set, especially for days when the sluice gates and (or) controlling works are in operation. Thus, if all the data are used, the resulting set of equations provides more robust estimations than if the data sets are kept separate.

In table 5, regression coefficients and standard errors are listed for a multiple linear regression of adjusted AVM discharges at Romeoville on the basis of MWRD discharge estimates at Lockport for the various discharge regimes. For days when the sluice gates and (or) controlling works are in operation, the regression-coefficient values and their differences between the Sarasota AVM period of operation and the ORE AVM period of operation are similar to those reported for the unadjusted data in table 2 despite the differences in the periods used to derive the coefficients in tables 2 and 5.

Table 5.--Regression coefficients and standard errors of the multiple linear regression of adjusted acoustic-velocity-meter discharges at Romeoville, Ill., approximated on the basis of discharge estimates made by the Metropolitan Water Reclamation District of Greater Chicago for Lockport, Ill., for the various discharge regimes (combinations of outlet works); separate equations are provided for the periods of operation for the Sarasota and ORE acoustic velocity meters

[AVM, acoustic velocity meter; a_0, intercept of the multiple linear regression; a_1, regression coefficient between the AVM discharge and the Metropolitan Water Reclamation District of Greater Chicago (MWRD) estimate of turbine, lockage, and leakage discharge for the given data set; a_2, regression coefficient between the AVM discharge and the MWRD estimate of sluice-gate discharge for the given data set; a_3, regression coefficient between the AVM discharge and the MWRD estimate of controlling-works discharge; all coefficients are used to estimate daily mean discharge, in cubic feet per second; coef., coefficient; --, no value calculated]

Discharge regime	Regression coefficient	Sarasota AVM[1] Number of days	Sarasota AVM[1] Coef. value	Sarasota AVM[1] Standard error	ORE AVM[2] Number of days	ORE AVM[2] Coef. value	ORE AVM[2] Standard error
Turbine, lockage, and leakage	a_0	569	-58.52	26.75	777	147.9	18.79
	a_1		1.168	.00863		1.104	.00651
Sluice gates	a_0	92	99.32	110.1	156	745.9	98.33
	a_1		1.145	.0313		1.023	.0294
	a_2		.8316	.0252		.4486	.0139
Controlling works	a_0	14	2,055	1,530	32	3,426	725.7
	a_1		.9037	.4460		.4645	.1920
	a_2		.6692	.0521		.3802	.0371
	a_3			--	--	.3264	.0560

[1]Period of operation considered October 2, 1986, through November 2, 1988.
[2]Period of operation considered November 18, 1988, through September 30, 1991.

For days of TLL discharge only, the difference in the slope (a_1) and intercept (a_0) of the regression equations between the Sarasota AVM period of operation and the ORE AVM period of operation is more than 7 standard errors. This is a significant change relative to the previous comparison of the two AVM's for which the difference was less than 2 standard errors. Therefore, statistically, the hypothesis that the adjusted Sarasota AVM and ORE AVM discharges are from the same population for days of TLL discharges only is questionable. From a practical point of view, however, the regression equations for one AVM provide a reasonably good estimator of the data for the other AVM. Estimation of discharges for the ORE AVM period by use of the Sarasota AVM period regression equations yields a mean and standard deviation of the residuals equal to 29.2 and 157.8 ft^3/s, respectively, for days of TLL discharge only. Estimation of discharges for the Sarasota AVM period by use of the ORE AVM period regression equations yields a mean and standard deviation of the residuals of -14.1 and 165.1 ft^3/s, respectively, for days of TLL discharge only. The mean values of the residuals are less than 1 percent of the average AVM-measured discharge for each period. The standard deviations of the residuals are similar to the standard error of the linear regression equations for the same period: 165.1 to 157.9 ft^3/s for the Sarasota AVM period and 157.8 to 149.0 ft^3/s for the ORE AVM period. The mean and standard deviation of the ARD for days of TLL discharge only are 1.26 and 1.02 percent, respectively, for the period of Sarasota AVM operation and 1.75 and 1.50 percent, respectively, for the period of ORE AVM operation.

The consistency of the adjusted discharges for the Sarasota AVM and ORE AVM periods for days with SG and (or) CW discharges is best shown graphically. This comparison is facilitated by the assumption that the linear regression between AVM discharge measurements and MWRD discharge estimates at Lockport for days of TLL discharge only define an error relation for the TLL discharge regime. This error relation is assumed to hold for the TLL outlets even on days when the sluice gates and (or) controlling works are active. (The validity of this assumption is discussed in the section on Form of the Estimation Equations.) Subtraction of the corrected TLL discharges from the AVM discharge estimate yields corrected discharges through the SG and (or) CW. The corrected SG and (or) SG+CW discharge can then be compared to the MWRD estimates of these discharges. The corrected SG discharge and the MWRD-estimated SG discharge for days when the CW was not operating are shown in figure 9. The corrected SG+CW discharge and the MWRD-estimated SG+CW discharge are shown in figure 10. These figures show similar values and variabilities of corrected SG discharge compared to MWRD SG discharge and corrected SG+CW discharge and the MWRD SG+CW discharge for the Sarasota AVM and ORE AVM periods of operation. The SG data for the ORE AVM period that appear to be significantly different from the Sarasota period are the six highest MWRD SG daily mean discharge estimates. For these 6 days, the SG's were discharging at a high rate that in all other cases were associated with days when the CW also was operating. Therefore, this inconsistency is because of high discharge rates and not because of changes in AVM measurements relative to MWRD discharge estimates.

Estimation of discharges for the period of Sarasota AVM operation by the set of regression equations developed for the ORE AVM period of operation and for the period of ORE AVM operation by the set of regression equations developed for the Sarasota AVM period yields the following summary statistics:

	Mean (ft^3/s)		Standard deviation (ft^3/s)	
AVM	Measured	Estimated	Measured	Estimated
Sarasota	3,817	3,768	1,590	1,343
ORE	3,645	3,718	1,631	1,957

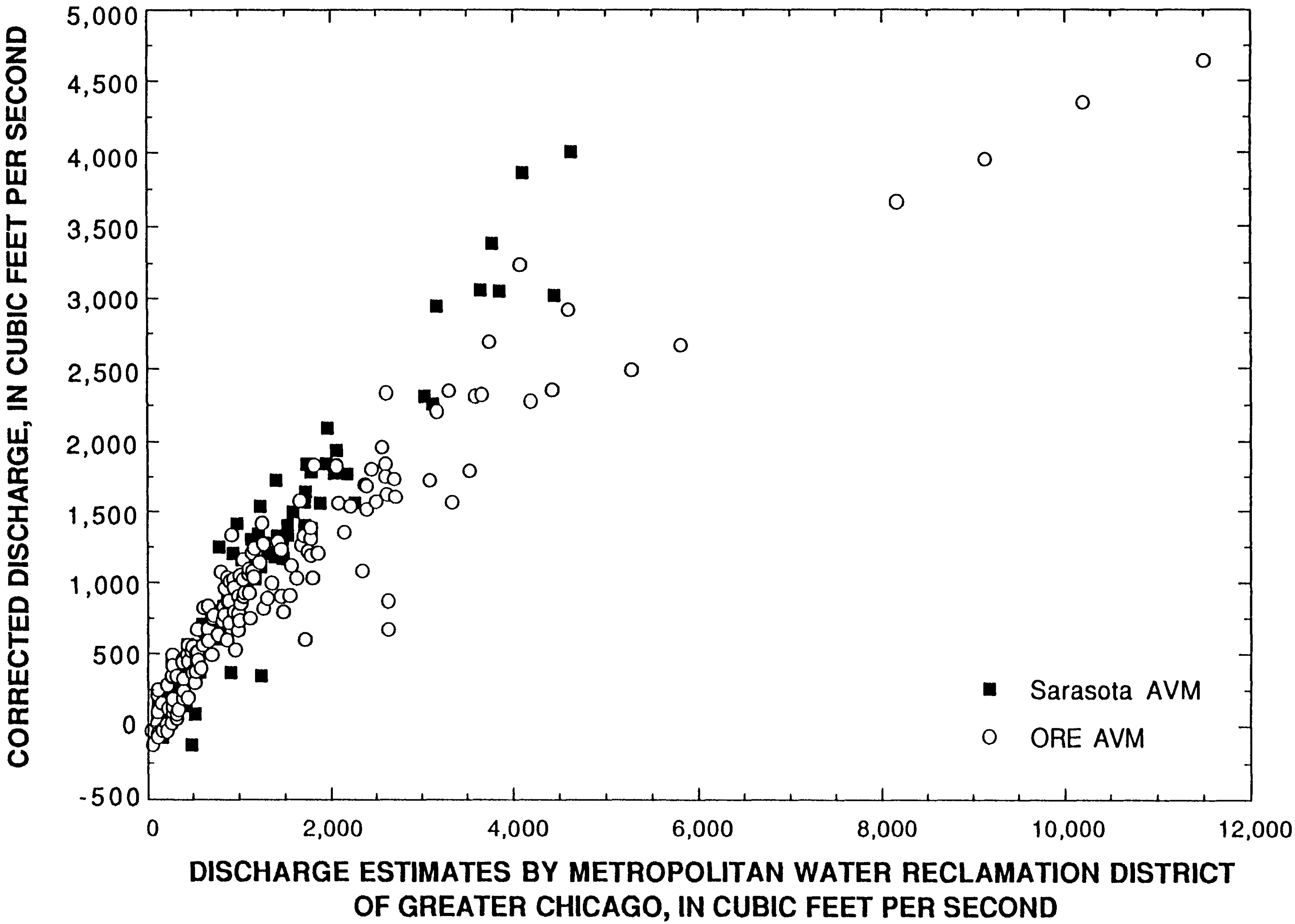

Figure 9.--Sluice-date discharge estimates by Metropolitan Water Reclamation District of Greater Chicago and corrected sluice-gate discharge estimated from the acoustic-velocity-meter (AVM) measurements.

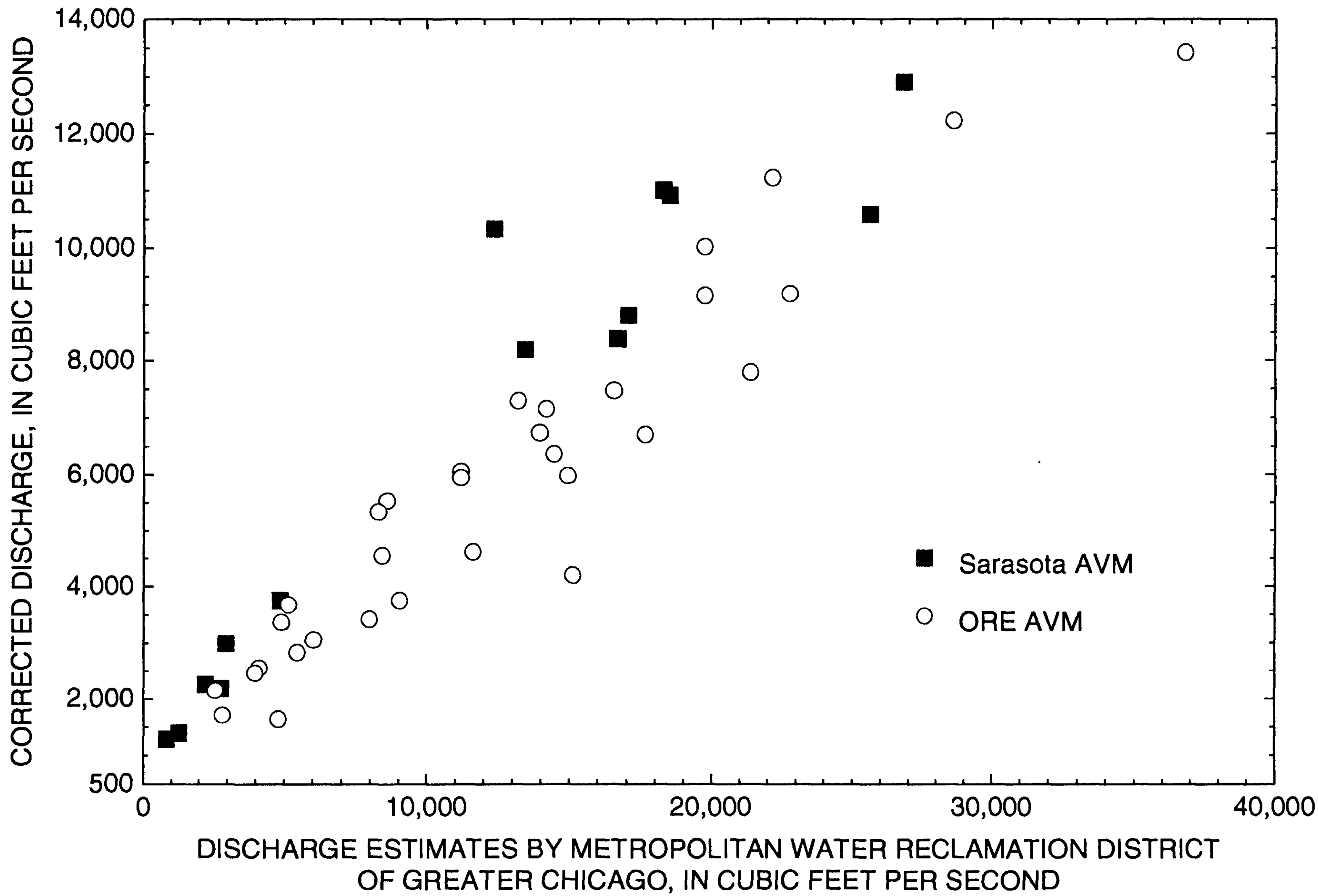

Figure 10.--Sluice-gate plus controlling-works discharge estimates by Metropolitan Water Reclamation District of Greater Chicago and corrected sluice-gate plus controlling-works discharge estimated from the acoustic-velocity-meter (AVM) measurements.

In each case, the error in the estimated mean is 2 percent or less. The mean and standard deviation of the ARD for all days are 2.22 and 2.96 percent, respectively, for the period of Sarasota AVM operation and 3.14 and 4.72 percent, respectively, for the period of ORE AVM operation. Considering the overall accuracy of estimating discharges for one period by use of the regression equations for the other period and the comparisons of figures 9 and 10, it is reasonable to combine the Sarasota AVM and ORE AVM discharge measurements when developing the equations for estimating the days of missing record. Further demonstration of the advantages of combining the two data sets is discussed in the section on Verification of Estimation Equations.

Form of the Estimation Equations

The Second Technical Committee (Espey and others, 1987) recommended that the data be subdivided into groups according to the discharge regime (that is, combination of outlet works in operation), and then the development of simple linear-regression equations between AVM and MWRD discharges for each discharge regime. The Corps (U.S. Army Corps of Engineers, 1989) went one step further by developing multiple linear-regression equations between AVM discharges and the discharge through each of the outlet-works components as given by equations 1-3. As discussed previously, this study followed the Corps' approach. However, the form of the regression equation for days when the CW was operating often appeared (tables 2 and 5) to be more of a "best fit of a particular data set" than a "model of the predictable behavior of the process," the latter being the goal of statistical-estimation-model development (Larimore and Mehra, 1985). This conclusion is evidenced by the large changes in regression-coefficient values as the discharge regime changes from sluice gates to controlling works.

A more physically based model (William Kirby, U.S. Geological Survey, Office of Surface Water, written commun., 1992), which might be a better estimator of "the predictable behavior of the process," also was developed and tested. In this physically based model, the linear-regression equation developed between AVM-measured discharges and MWRD discharge estimates for days when only TLL discharge occurs is assumed to define an error relation for the TLL discharge regime. This error relation is assumed to hold for the TLL outlets even on days when the sluice gates and (or) controlling works are active. Subtraction of the corrected TLL discharges from the AVM discharge estimates yields corrected discharges through the SG and (or) CW. Linear regression or multiple linear regression is then performed between the corrected discharge values and the MWRD estimates of the discharges through the outlet components.

The discharge through the turbines is not the same for days when the other outlet works are in operation as for days of only the turbines and lock operation. The headwater elevation is lower and the tailwater elevation is probably higher for the turbines on days when the other outlet works are in operation. On days with high flows, the headwater elevation can decrease as much as 5 ft, greatly changing the efficiency of the turbines and the error in the estimate of turbine discharge. The results of the multiple linear regression on days when the sluice gates, but not the controlling works, are in operation indicate that the error of holding the coefficient between TLL discharge and AVM discharge constant is not statistically significant. Thus, the hydraulic error of assuming the relation between MWRD and AVM discharge estimates of TLL discharge constant for all discharge regimes is probably small as well. Conversely, the high hydraulic uncertainties in the SG discharge estimates, shown by the large variation of corrected SG discharge relative to the MWRD-estimated discharge in figure 9, made separation of corrected SG and CW discharges unwise.

The regression coefficients and standard errors of the multiple linear-regression equations between the AVM discharges and the MWRD flow estimates and the number of days used to develop each equation are listed in table 6. These equations were derived using all AVM-measured discharges in water years 1987 through 1991. Further, the discharge regimes were altered slightly, such that the days with MWRD estimates of SG discharge greater than 5,000 ft^3/s were shifted to the CW discharge regime. This shift was made because, as shown in figures 9 and 10, these discharges through the SG were of a magnitude that in all other cases was associated with days of CW operation. The corrected SG+CW discharge and the MWRD-estimated SG+CW discharge for the CW discharge regime and the 6 days of MWRD-estimated SG discharge greater than 5,000 ft^3/s are shown in figure 11. These 6 days of high MWRD-estimated SG discharge show good agreement with the CW discharge regime.

Table 6.--Regression coefficients and standard errors of the multiple linear regression of adjusted acoustic-velocity-meter discharges at Romeoville, Ill., approximated on the basis of discharge estimates made by the Metropolitan Water Reclamation District of Greater Chicago for Lockport, Ill., for the various discharge regimes (combinations of outlet works)

[a_0, intercept of the multiple linear regression; a_1, regression coefficient between the acoustic-velocity-meter (AVM) discharge and the Metropolitan Water Reclamation District of Greater Chicago (MWRD) estimate of turbine, lockage, and leakage discharge for the given data set; a_2, regression coefficient between the AVM discharge and the MWRD estimate of sluice-gate discharge for the given data set; a_3, regression coefficient between the AVM discharge and the MWRD estimate of controlling-works discharge; all coefficients are used to estimate daily mean discharge in cubic feet per second; <, less than; >, greater than; ft^3/s, cubic feet per second]

Discharge regime	Coefficient	Number of days	Coefficient value	Standard error
Turbine, lockage, and leakage	a_0	1,346	75.48	15.59
	a_1		1.127	.00523
Sluice gates (< 5,000 ft^3/s)	a_0	242	245.0	80.27
	a_1		1.120	.0229
	a_2		.6831	.0187
Controlling works or sluice gates (> 5,000 ft^3/s)	a_0	52	2,584	807.0
	a_1		.6883	.2163
	a_2		.4167	.0435
	a_3		.3455	.0666

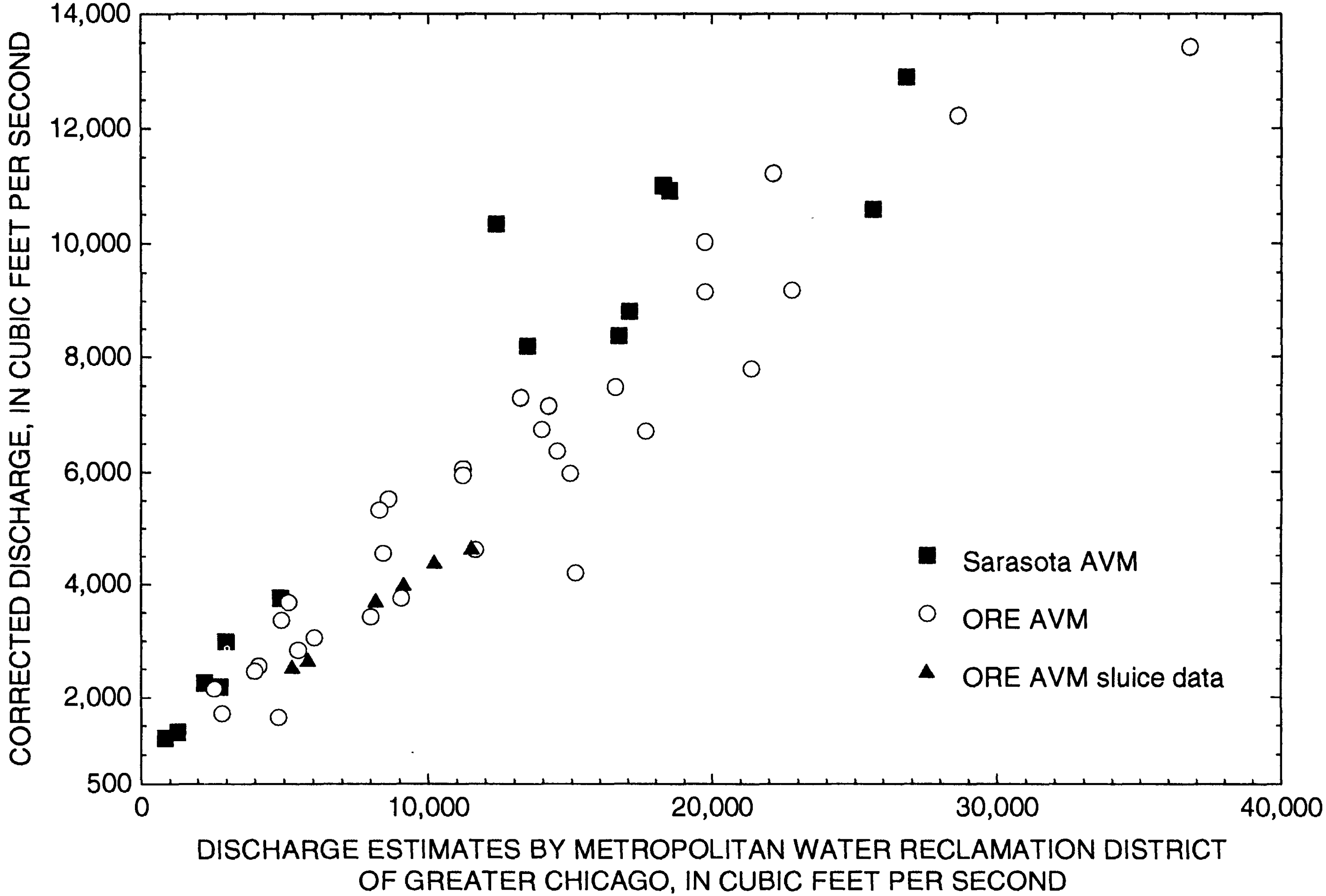

Figure 11.--Sluice-gate plus controlling-works discharge estimates by Metropolitan Water Reclamation District of Greater Chicago and corrected sluice-gate plus controlling-works discharge estimated from the acoustic-velocity-meter (AVM) measurements (includes the 6 days of estimated sluice-gate discharge greater than 5,000 cubic feet per second with no controlling-works discharge).

The approach of regression of the corrected discharges with the MWRD-estimated discharges resulted in the following equations for days with MWRD-estimated SG discharge less than 5,000 ft^3/s:

$$Q = 1.1270 \times Q_{TLL} + 0.6842 \times Q_{SG} + 219.7, \qquad (11)$$

and for days with MWRD-estimated SG discharge greater than 5,000 ft^3/s or CW in operation:

$$Q = 1.1270 \times Q_{TLL} + 0.4361 \times Q_{SG} + 0.3228 \times Q_{CW} + 1,086. \qquad (12)$$

It is interesting to note that all the coefficients in equation 11 are within 1 standard error of the values from multiple linear regression reported in table 6, whereas the coefficients in equation 12 are considerably different from the values in table 6. The standard errors of the equation (S_e) and the standard error of the equation as a fraction of mean flow for the given flow regime (S_e/Q_M) of the various equations are as follows:

[<, less than; >, greater than; ft^3/s, cubic feet per second]

	S_e (ft^3/s)	S_e/Q_M (percent)
Turbine, lockage, and leakage (table 6)	155.0	4.69
Turbine, lockage, leakage, and sluice gates (< 5,000 ft^3/s)		
Regression equation (table 6)	295.5	6.24
Corrected discharge equation (equation 11)	295.9	6.25
Turbine, lockage, leakage, sluice gates, and controlling works or sluice gates (> 5,000 ft^3/s)		
Regression equation (table 6)	1,195	12.5
Corrected discharge equation (equation 12)	1,245	13.1

The standard errors of equations 11 and 12 are nearly equal to those for the multiple linear-regression equations. Thus, it is clear that the equations derived from the corrected discharges provide nearly as close a fit to the AVM discharges as do the multiple linear-regression equations and a much better physical basis than the multiple linear-regression equations.

The residuals of either the multiple linear-regression equations or the equations derived from the corrected discharges are correlated in time (especially for the TLL discharge regime) and are not normally distributed. Similar results were found for the regression equations previously developed by the Corps (U.S. Army Corps of Engineers, 1989). Theoretically, this would invalidate the regression analyses performed in the sense that there is a better way to extract the maximum estimation capability from the given set of data (Troutman, 1985). That is, a model which incorporates the serial (temporal) correlation and transforms the residuals to be normally distributed would provide the maximum estimation capability from the given set of data. However, as pointed out by the Hydrologic Engineering Center (1990) in their review of the Corps (U.S. Army Corps of Engineers, 1989) regression equations, because the residuals are not independent or normally distributed does not mean that these regression equations should not be applied or accepted. The Hydrologic Engineering Center (1990) concluded that the regression equations

"...probably do not provide maximum likelihood estimates of the regression coefficients because of the failure of the residuals to meet certain stringent distributional requirements. However, the regression equations fit the data very well, and better than the previous attempts to develop regression relationships. Attempts to transform the data did not obtain a better distribution for the residuals or a better fit, nor do the transformed equations provide better forecasts. Consequently, the recommendation is to accept Chicago's proposed regressions as being the best available."

From this it is clear that equations derived for transformed data are unlikely to have improved properties or to provide improved estimates. Further, the regression equations and equations derived from the corrected discharges fit the data very closely, and, in the case of the equations derived from the corrected discharges, from a more correct physical basis than the regression equations that have been developed previously for the discharge through the Canal (Espey and others, 1987; U.S. Army Corps of Engineers, 1989).

Verification of Estimation Equations

The ultimate test of the regression equations and equations derived from corrected discharges is to estimate data not used in equation development; that is, verification of these equations. Data for water year 1992 were not used in the derivation of the estimation equations because these data have not been finalized and approved for final distribution. However, preliminary discharge estimates for the Lockport powerhouse and controlling works and the AVM at Romeoville are available for the period October 1, 1991, through May 31, 1992. The relatively small errors in these data (on random days) should not affect the use of these data in verifying the general estimation performance of the regression equations and the equations derived from corrected discharges.

The statistics of the AVM-measured discharges and the two sets of estimated discharges for the 238-day period, which included 66 days of SG operation (no discharges greater than 5,000 ft^3/s) and 6 days of CW operation, in the 1992 water year, are given below.

	Mean (cubic feet per second)	Standard deviation (cubic feet per second)	Skewness coefficient
AVM measurements	3,592	1,708	1.52
Regression equations estimates	3,594	1,598	1.45
Corrected discharge equations estimates	3,600	1,620	1.51

The standard deviation of the residuals of the estimated series are 216 ft^3/s for the regression equations and 206 ft^3/s for the equations derived from corrected discharges. The hydrographs of the measured and estimated discharges for the regression equations and the equations derived from corrected discharges are shown in figures 12 and 13, respectively.

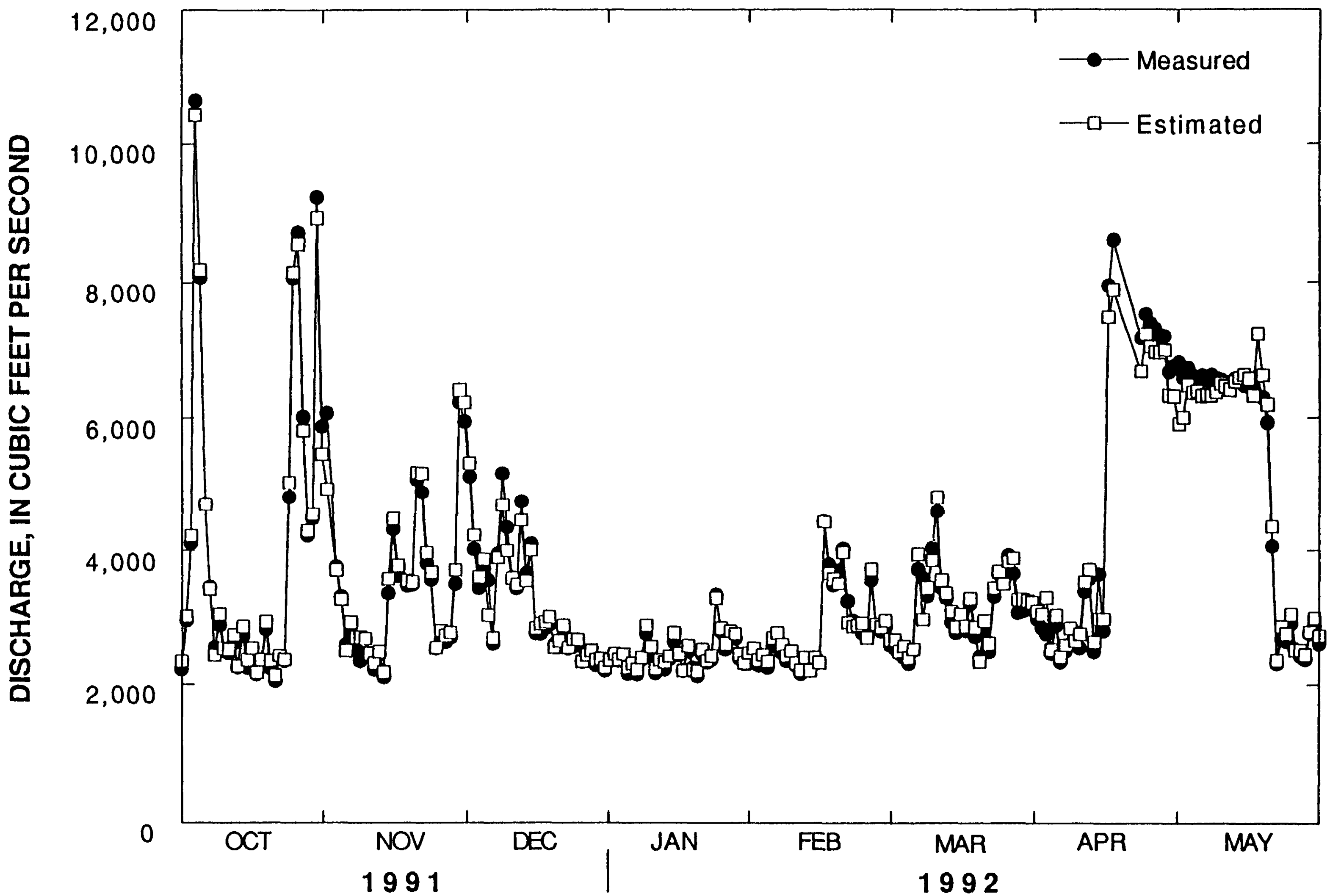

Figure 12.--Daily mean discharge estimated by the best-fit multiple linear-regression equations and the measured daily mean discharge for October 1, 1991, through May 31, 1992.

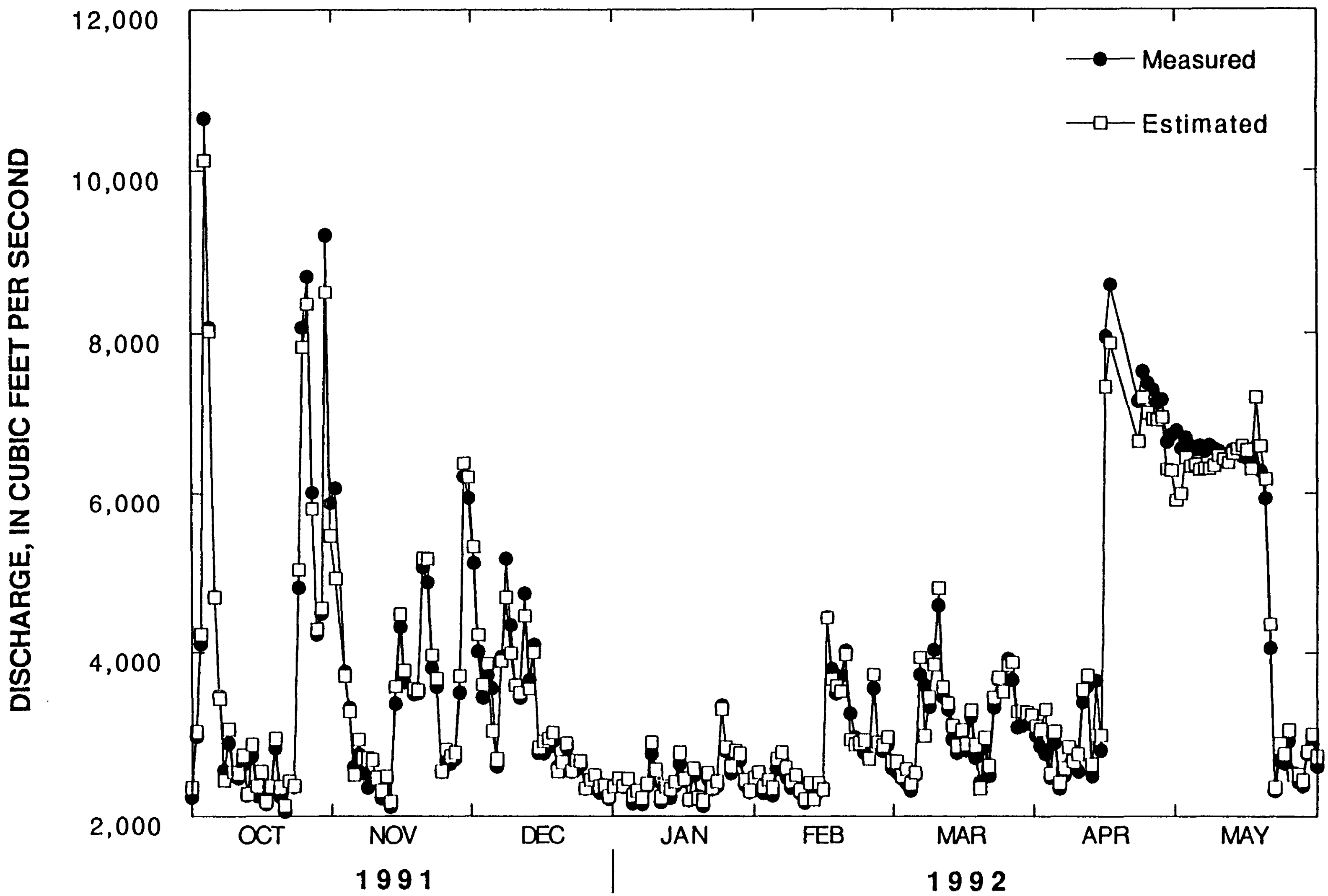

Figure 13.--Daily mean discharge estimated by the regression equations derived from corrected discharges and the measured daily mean discharge for October 1, 1991, through May 31, 1992.

Figures 12 and 13 and the statistics presented above clearly indicate that either equation offers an excellent estimation of discharges for October 1, 1991, through May 31, 1992. This is an especially stringent comparison because from April 15 through May 20, 1992, the Corps was performing repairs on the lock and the SG's were used to keep water levels low. Thus, the comparison period includes a disproportionate number of days of SG operation, and the hydraulic conditions for SG operation are different from the typical operation of the SG for release of high flows caused by stormwater runoff. Therefore, the comparison period represents a significantly perturbed condition relative to the calibration data, which forms the ideal type of verification data (Thomann, 1982).

The verification period also was estimated by three other sets of equations. Those sets were derived with the 6 days of MWRD-estimated discharge through the SG greater than 5,000 ft^3/s still included in the SG discharge regime. The sets are (1) regression equations and (2) equations derived from corrected discharges. The three cases considered for development of the equations are (1) Sarasota AVM discharge, (2) ORE AVM discharge, and (3) all AVM discharge. The mean, standard deviation, and skewness coefficient of the measured and estimated data and the standard deviation of residuals of the estimated data are shown in table 7. The equations derived from all the AVM data provide a better estimation than those derived from the data from only one AVM as shown in table 7. Further, comparison of values in table 7 with the results reported previously indicates that the shifting of the 6 days of MWRD-estimated high SG discharge also improves the estimates obtained.

Table 7.--Discharge statistics for October 1, 1991, through May 31, 1992, for the measured discharges at Romeoville, Ill., and the estimated discharges using three sets of regression equations and equations derived from corrected discharges

[AVM, acoustic velocity meter; ft^3/s, cubic feet per second]

Discharge series	Mean (ft^3/s)	Standard deviation (ft^3/s)	Skewness coefficient	Residual standard deviation (ft^3/s)
Measured	3,592	1,708	1.52	
Estimated regression, Sarasota AVM data	3,664	1,839	1.71	270
Estimated corrected, Sarasota AVM data	3,646	1,791	1.60	212
Estimated regression, ORE AVM data	3,537	1,442	1.43	348
Estimated corrected, ORE AVM data	3,548	1,484	1.51	317
Estimated regression, all data	3,572	1,555	1.52	267
Estimated corrected, all data	3,579	1,581	1.60	266

Estimation of Missing Record

The AVM's were not operational for a total of 545 days in water years 1986 through 1991. The entire 1986 water year makes up the majority of the non-operational period; all periods are listed in appendix 1. Because of the closeness of fit to the data for water years 1987 through 1991, estimation accuracy for the verification period of October 1, 1991, through May 31, 1992, and physical basis, the equations derived from corrected discharges were used to estimate the missing record. The complete estimated record is given in appendix 2.

Future Considerations

The equations derived from corrected discharges are valid for estimating missing record only up to August 20, 1992. In February 1992, the MWRD installed AVM's in the intakes to the turbines at Lockport. These AVM's started collecting data on March 19, 1992, and, beginning on August 21, 1992, the turbine AVM discharge measurements replaced the flow estimates from the turbine rating tables in the official MWRD report of flows at Lockport. Thus, estimation of missing record at the Romeoville AVM in the future will require the derivation of new equations of the form developed in this or similar studies. These equations cannot be developed until sufficient data have been collected at the Lockport turbine AVM's. Because the controlling works and (or) sluice gates are used sparingly in any given year, it could take several years to collect sufficient data for derivation of accurate new estimation equations. In the interim, a new relation between the MWRD rating estimate of turbine discharges and the true turbine discharges measured at the turbine AVM's could be developed for data from March through August 1992, and the equations derived from corrected discharges could then be reworked.

SUMMARY AND CONCLUSIONS

Discharge and regression analyses of acoustic-velocity-meter (AVM) data were done to obtain the most accurate estimates of discharge possible for the Chicago Sanitary and Ship Canal at Romeoville, Ill., for water years 1986-91. The analyses included (1) a check of the consistency of discharge estimates made by two AVM's used during this period, (2) adjustment of the discharge estimates to account for errors in the Canal width and depth used prior to Canal geometry measurement in June 1991, (3) development and verification of equations for estimating discharge on days when the AVM was not functioning properly, and (4) estimation of discharge for all days when the AVM's were not functioning properly.

The examination of the consistency of discharge estimates made by the two AVM's involved three analyses.

1. The discharge series estimated by the Sarasota AVM and the ORE AVM were compared for changes in the mean and variance by the t-test and F-test, respectively, and in the discharge-duration curves for several different combinations of operating outlet works. Trends in the discharge series

between the periods of Sarasota AVM and ORE AVM operation were compared to those trends at a nearby streamflow-gaging station (Des Plaines River at Riverside). Natural variations in discharge between the periods of operation of the two AVM's are far larger than any likely difference between the two meters.

2. Multiple linear-regression equations were derived relating AVM discharge estimates at Romeoville and Metropolitan Water Reclamation District of Greater Chicago (MWRD) discharge estimates at Lockport for the periods of operation of the two AVM's. The regression equations for the Sarasota AVM were used to estimate the ORE AVM period of operation, and the regression equations for the ORE AVM were used to estimate the Sarasota AVM period of operation. The regression equations developed and the estimates made applying these equations indicated that the regression equations for the two AVM's were practically indistinguishable.

3. Vertical velocity-distribution measurements made by the two AVM's were compared. The vertical velocity distributions measured by the two AVM's were consistent and within the range of values expected from open-channel flow theory.

In summary, no difference in the discharge computed using the two AVM's can be supported, and no correction factor is needed to adjust one AVM to be consistent with the other AVM.

The measurements of the Canal width and depth performed on June 4 and 5, 1991, indicated that the channel between the AVM transducers that measure velocity was 1.55 ft deeper and 2 ft narrower than had been previously determined from the original engineering plans and measurements of width made from the Romeoville Road bridge. Corrections for these errors were made easily for the ORE AVM data by reexecuting the computer programs developed by the USGS for estimating discharge at Romeoville, on the basis of AVM velocity and gage-height measurements. The Sarasota AVM discharge estimates were not corrected as easily because they were calculated internally by the AVM and output by the AVM to the USGS. The correction procedure used was developed on the basis of the cross-sectional average velocity computed from 15-minute and (or) daily mean discharges output by the Sarasota AVM, the estimated vertical velocity distribution, and discharge calculation by the method of horizontal slices.

Two different forms of equations for estimating discharge at Romeoville on the basis of MWRD discharge estimates at Lockport were compared. The first form was from standard multiple-linear regression between AVM discharge estimates at Romeoville and MWRD estimates of discharge at Lockport through the various outlet components--turbines, lockage, and leakage (TLL); powerhouse sluice gates; and controlling works. The error in the MWRD estimates of sluice-gate and controlling-works discharge is potentially very large. In the second form, the regression relation between MWRD estimates of TLL discharge at Lockport and AVM discharge estimates at Romeoville derived for days when the sluice gates and (or) controlling works were not in operation was used to define an error relation for the TLL discharge regime. This error relation was assumed to hold for the TLL outlets even on days when the sluice gates and (or) controlling works were active. Subtraction of the corrected TLL discharge from the AVM discharge estimates yielded corrected discharges through the sluice gates and (or) controlling works. Regression equations were then developed between the corrected discharges and the MWRD estimates of discharge through these outlet components. The equations derived from corrected discharges performed as well as the first form of regression equations in terms of closeness of fit for the calibration period (October 2, 1986, through September 30, 1991) and estimation quality for the verification period (October 1, 1991, through May 31, 1992). The equations derived from the corrected discharges estimated the mean, standard deviation, and skewness coefficient of the daily mean discharges at Romeoville for the verification period within 0.22, 5.15, and 0.66 percent, respectively. This was considered to be an excellent verification.

The corrected discharges were used to estimate discharge at Romeoville for days when the AVM was not operational because of their excellent verification and strong physical basis. The discharge at Romeoville was estimated for 545 days on which the AVM was not operational. The corrected discharges have been entered into the discharge record for the station.

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APPENDIXES

Appendix 1: History of inoperative periods for the acoustic velocity meter (AVM) at Romeoville, water years 1984-91

DATE	REMARKS
June 12, 1984	Sarasota AVM installed and operational.
November 29, 1984	Printer failed to advance paper.
March 17, 1985	Printer jammed.
February 23-24, 1985	Stage below the minimum AVM threshold value, no discharges calculated.
March 21 - April 18, 1985	Underwater cable connecting the transducers cut by a barge on March 21. The wires were reconnected and a repairman replaced the coefficients in the AVM unit, CPU timer module, and path-timer module on April 18.
April 19 - November 5, 1985	Various system problems during this period caused the AVM record to be questionable during this period. The system problems included underwater cable cut by barge on June 6-7; signal detector module failed on June 9-10; electrical power to the AVM cut off on June 27-28; AVM failed on August 1-12 because of a power surge from an electrical storm; and CPU timer module improperly set to use the last 2 minutes to calculate the 15-minute discharges.
November 6, 1985 - September 22, 1986	The CPU timer module properly reset on November 5, but operation problems resulted in low measurements of stage and velocity and, thus, in low values of computed discharge.
September 23 - October 1, 1986	On September 22, Sarasota personnel repaired the malfunctioning components of the AVM. In this period, however, the AVM was subjected to power surges.
April 24-25, 1987	AVM failed because of a power surge.
May 13-15, 1987	AVM failed because of a power surge.
December 31, 1987 - January 12, 1988	Power to the gage shut off.
January 15, 1988	ROM board replaced.
March 17 - May 24, 1988	A combination of receiver board and transducer malfunction and failure. The receiver board was replaced and reset, and all four velocity transducers and the depth transducer were replaced.

Appendix 1: History of inoperative periods for the acoustic velocity meter (AVM) at Romeoville, water years 1984-91--Continued

DATE	REMARKS
November 3-17, 1988	Installation of ORE AVM.
January 31 - February 3, 1989	AVM failed because of power surge.
June 12-14, 1989	Repair of the uplooking transducer for gage-height measurement.
August 22-23, 1989	AVM failed because of power surge.
September 26 - October 6, 1989	Underwater cables cut by a barge.
October 10-13, 1989	Transducer assembly knocked out of alignment by a barge.
November 15-21, 1989	Bad velocity measurements obtained from the transducers, and the transducers fell from their mountings into the canal.
March 16-19, 1990	Transducer assembly knocked out of alignment by a barge.
April 29 - May 1, 1990	A short circuit in the junction box caused the AVM to shut down.
May 4-8, 1990	No gage-height record because of equipment malfunction.
May 9-30, 1990	Underwater cables cut by a barge.
June 14, 1990	AVM transceiver damaged by lightning.
March 27, 1991	AVM was down because of a loss of power caused by high winds.
April 20-24, 1991	AVM was down because of the measurement section of the AVM locking up.
May 31 - June 3, 1991	AVM was down because of the measurement section of the AVM locking up.

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative

[MWRD, Metropolitain Water Reclamation District of Greater Chicago; USGS, U.S. Geological Survey; no values are shown for days with no flow through sluice gates or contolling works]

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
10/01/85	2,524	264	100			2,888	3,330
10/02/85	2,403	297	100			2,800	3,231
10/03/85	3,636	462	100	266		4,464	5,133
10/04/85	3,004	396	100			3,500	4,020
10/05/85	3,014	396	100			3,510	4,031
10/06/85	3,003	363	100			3,466	3,982
10/07/85	2,088	396	100			2,584	2,988
10/08/85	3,687	330	100			4,117	4,715
10/09/85	4,203	396	100			4,699	5,371
10/10/85	2,999	363	100			3,462	3,977
10/11/85	2,605	396	100			3,101	3,570
10/12/85	3,667	396	100			4,163	4,767
10/13/85	2,880	330	100			3,310	3,806
10/14/85	2,691	396	100			3,187	3,667
10/15/85	2,428	330	100			2,858	3,296
10/16/85	2,799	330	100			3,229	3,714
10/17/85	2,630	363	100			3,093	3,561
10/18/85	3,273	330	100	2,703	458	6,864	6,586
10/19/85	3,493	264	100	10,021	3,091	16,969	10,801
10/20/85	3,383	429	100			3,912	4,484
10/21/85	3,243	396	100			3,739	4,289
10/22/85	3,091	297	100			3,488	4,006
10/23/85	3,226	396	100	969	386	5,077	5,828
10/24/85	2,775	396	100	468		3,739	4,226
10/25/85	3,349	297	100			3,746	4,297
10/26/85	3,206	363	100			3,669	4,210
10/27/85	2,911	363	100			3,374	3,878
10/28/85	2,682	396	100			3,178	3,657
10/29/85	2,542	363	100			3,005	3,462
10/30/85	2,403	396	100			2,899	3,343
10/31/85	2,772	297	100			3,169	3,647
11/01/85	3,673	297	100	2,515		6,585	6,527
11/02/85	3,670	231	100	2,621		6,622	6,522
11/03/85	3,880	297	100			4,277	4,896
11/04/85	2,729	264	100			3,093	3,561

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
11/05/85	2,718	231	100			3,049	3,512
11/06/85	2,878	330	100			3,308	3,804
11/07/85	2,550	231	100			2,881	3,322
11/08/85	2,219	231	100			2,550	2,949
11/09/85	2,422	264	100	3,693	897	7,376	6,126
11/10/85	4,192	264	100	3,449		8,005	7,714
11/11/85	4,362	363	100	376		5,201	5,915
11/12/85	4,165	363	100	439		5,067	5,736
11/13/85	3,565	231	100	332		4,228	4,838
11/14/85	2,899	330	100			3,329	3,827
11/15/85	4,106	330	100			4,536	5,188
11/16/85	4,233	231	100	1,380		5,944	6,308
11/17/85	4,019	264	100	539		4,922	5,528
11/18/85	4,009	363	100	4,592		9,064	8,401
11/19/85	3,518	231	100	11,876	970	16,695	10,916
11/20/85	3,193	231	100	8,971		12,495	8,970
11/21/85	4,102	363	100	2,106		6,671	6,805
11/22/85	4,140	198	100	267		4,705	5,404
11/23/85	4,165	264	100			4,529	5,180
11/24/85	3,427	363	100			3,890	4,460
11/25/85	2,594	363	100			3,057	3,521
11/26/85	3,068	264	100			3,432	3,943
11/27/85	2,801	396	100			3,297	3,791
11/28/85	2,186	363	100			2,649	3,061
11/29/85	2,261	363	100			2,724	3,145
11/30/85	2,633	264	100			2,997	3,453
12/01/85	4,032	330	100	1,846		6,308	6,511
12/02/85	4,116	330	100			4,546	5,199
12/03/85	3,581	429	100			4,110	4,707
12/04/85	3,138	264	100			3,502	4,022
12/05/85	3,009	363	100			3,472	3,988
12/06/85	2,776	297	100			3,173	3,651
12/07/85	2,177	363	100			2,640	3,051
12/08/85	2,197	297	100			2,594	2,999
12/09/85	2,214	330	100			2,644	3,055

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
12/10/85	2,631	363	100			3,094	3,562
12/11/85	3,083	363	100			3,546	4,072
12/12/85	2,721	330	100			3,151	3,627
12/13/85	2,600	363	100			3,063	3,527
12/14/85	1,655	363	100			2,118	2,462
12/15/85	2,039	297	100			2,436	2,821
12/16/85	2,281	330	100			2,711	3,131
12/17/85	2,147	297	100			2,544	2,942
12/18/85	2,275	363	100			2,738	3,161
12/19/85	2,016	264	100			2,380	2,758
12/20/85	2,533	231	100			2,864	3,303
12/21/85	2,092	165	100			2,357	2,732
12/22/85	1,851	165	100			2,116	2,460
12/23/85	2,010	165	100			2,275	2,639
12/24/85	2,367	297	100			2,764	3,190
12/25/85	2,089	297	100			2,486	2,877
12/26/85	2,263	330	100			2,693	3,110
12/27/85	2,116	297	100			2,513	2,908
12/28/85	2,116	297	100			2,513	2,908
12/29/85	2,011	231	100			2,342	2,715
12/30/85	2,407	198	100			2,705	3,124
12/31/85	1,860	231	100			2,191	2,545
01/01/86	1,800	231	100			2,131	2,477
01/02/86	2,041	297	100			2,438	2,823
01/03/86	2,098	231	100			2,429	2,813
01/04/86	1,917	231	100			2,248	2,609
01/05/86	1,901	297	100			2,298	2,665
01/06/86	1,747	297	100			2,144	2,492
01/07/86	2,194	330	100			2,624	3,033
01/08/86	2,207	396	100			2,703	3,122
01/09/86	1,792	264	100			2,156	2,505
01/10/86	1,227	264	100			1,591	1,868
01/11/86	2,029	231	100			2,360	2,735
01/12/86	1,856	264	100			2,220	2,577
01/13/86	1,538	198	100			1,836	2,145

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
01/14/86	1,957	165	100			2,222	2,580
01/15/86	1,873	264	100			2,237	2,596
01/16/86	1,824	231	100			2,155	2,504
01/17/86	2,112	297	100			2,509	2,903
01/18/86	2,144	264	100			2,508	2,902
01/19/86	2,193	165	100			2,458	2,846
01/20/86	2,548	264	100			2,912	3,357
01/21/86	1,594	363	100			2,057	2,394
01/22/86	1,593	363	100			2,056	2,392
01/23/86	1,765	264	100			2,129	2,475
01/24/86	1,836	363	100			2,299	2,666
01/25/86	1,878	231	100			2,209	2,565
01/26/86	1,922	330	100			2,352	2,726
01/27/86	2,014	264	100			2,378	2,755
01/28/86	1,948	297	100			2,345	2,718
01/29/86	1,675	429	100			2,204	2,559
01/30/86	1,604	264	100			1,968	2,293
01/31/86	2,310	165	100			2,575	2,978
02/01/86	2,623	231	100			2,954	3,405
02/02/86	1,819	198	100			2,117	2,461
02/03/86	3,333	264	100			3,697	4,242
02/04/86	4,372	297	100	915		5,684	6,220
02/05/86	4,146	297	100			4,543	5,195
02/06/86	3,580	264	100			3,944	4,520
02/07/86	2,740	165	100			3,005	3,462
02/08/86	2,799	231	100			3,130	3,603
02/09/86	2,001	330	100			2,431	2,815
02/10/86	2,455	330	100			2,885	3,327
02/11/86	2,030	330	100			2,460	2,848
02/12/86	2,113	231	100			2,444	2,830
02/13/86	2,433	297	100			2,830	3,265
02/14/86	1,861	330	100			2,291	2,657
02/15/86	1,999	297	100			2,396	2,776
02/16/86	2,477	165	100			2,742	3,166
02/17/86	2,229	132	100			2,461	2,849

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
02/18/86	3,736	165	100			4,001	4,585
02/19/86	4,388	231	100			4,719	5,394
02/20/86	4,389	330	100			4,819	5,506
02/21/86	2,924	330	100			3,354	3,855
02/22/86	2,909	330	100			3,339	3,838
02/23/86	2,113	231	100			2,444	2,830
02/24/86	2,344	396	100			2,840	3,276
02/25/86	2,203	297	100			2,600	3,006
02/26/86	2,283	297	100			2,680	3,096
02/27/86	2,793	297	100			3,190	3,671
02/28/86	1,967	297	100			2,364	2,740
03/01/86	2,124	264	100			2,488	2,879
03/02/86	1,992	264	100			2,356	2,731
03/03/86	2,137	297	100			2,534	2,931
03/04/86	2,229	297	100			2,626	3,035
03/05/86	2,754	330	100			3,184	3,664
03/06/86	3,212	330	100			3,642	4,180
03/07/86	2,401	297	100			2,798	3,229
03/08/86	2,185	264	100			2,549	2,948
03/09/86	2,351	297	100			2,748	3,172
03/10/86	4,007	231	100	1,003		5,341	5,795
03/11/86	3,590	297	100			3,987	4,569
03/12/86	3,874	297	100			4,271	4,889
03/13/86	3,282	297	100			3,679	4,222
03/14/86	2,708	363	100			3,171	3,649
03/15/86	2,798	330	100			3,228	3,713
03/16/86	2,380	363	100			2,843	3,280
03/17/86	2,601	231	100			2,932	3,380
03/18/86	3,383	198	100			3,681	4,224
03/19/86	3,207	297	100			3,604	4,137
03/20/86	3,521	231	100			3,852	4,417
03/21/86	3,016	231	100			3,347	3,848
03/22/86	2,613	264	100			2,977	3,430
03/23/86	2,571	99	100			2,770	3,197
03/24/86	2,303	99	100			2,502	2,895

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
03/25/86	2,292	165	100			2,557	2,957
03/26/86	2,258	165	100			2,523	2,919
03/27/86	2,157	330	100			2,587	2,991
03/28/86	1,887	198	100			2,185	2,538
03/29/86	1,972	198	100			2,270	2,634
03/30/86	1,964	297	100			2,361	2,736
03/31/86	1,906	396	100			2,402	2,782
04/01/86	2,375	363	100			2,838	3,274
04/02/86	1,929	363	100			2,392	2,771
04/03/86	2,277	297	100			2,674	3,089
04/04/86	2,070	297	100			2,467	2,856
04/05/86	2,171	231	100			2,502	2,895
04/06/86	1,867	297	100			2,264	2,627
04/07/86	2,040	264	100			2,404	2,785
04/08/86	1,941	330	100			2,371	2,748
04/09/86	1,862	330	100			2,292	2,658
04/10/86	1,993	231	100			2,324	2,695
04/11/86	1,717	297	100			2,114	2,458
04/12/86	2,101	330	100			2,531	2,928
04/13/86	1,999	330	100			2,429	2,813
04/14/86	3,085	396	100			3,581	4,111
04/15/86	2,488	231	100			2,819	3,252
04/16/86	2,159	363	100			2,622	3,030
04/17/86	1,943	330	100			2,373	2,750
04/18/86	2,043	363	100			2,506	2,900
04/19/86	2,181	363	100			2,644	3,055
04/20/86	1,790	396	100			2,286	2,652
04/21/86	2,286	330	100			2,716	3,136
04/22/86	1,820	264	100			2,184	2,537
04/23/86	2,079	297	100			2,476	2,866
04/24/86	1,805	429	100			2,334	2,706
04/25/86	2,385	396	100			2,881	3,322
04/26/86	2,572	330	100			3,002	3,459
04/27/86	2,189	396	100			2,685	3,101
04/28/86	2,516	330	100			2,946	3,396

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
04/29/86	2,035	330	100	318		2,783	3,215
04/30/86	4,029	264	100	2,480		6,873	6,867
05/01/86	2,179	429	100			2,708	3,127
05/02/86	2,162	363	100			2,625	3,034
05/03/86	2,240	330	100			2,670	3,084
05/04/86	2,163	330	100			2,593	2,998
05/05/86	1,947	330	100			2,377	2,754
05/06/86	2,732	429	100			3,261	3,751
05/07/86	1,971	330	100			2,401	2,781
05/08/86	2,005	363	100			2,468	2,857
05/09/86	1,856	396	100			2,352	2,726
05/10/86	2,025	363	100			2,488	2,879
05/11/86	2,461	231	100			2,792	3,222
05/12/86	2,001	297	100			2,398	2,778
05/13/86	2,831	264	100			3,195	3,676
05/14/86	2,400	330	100			2,830	3,265
05/15/86	3,303	363	100			3,766	4,320
05/16/86	2,877	231	100			3,208	3,691
05/17/86	3,960	264	100	3,767	91	8,182	7,631
05/18/86	4,190	330	100	1,738		6,358	6,616
05/19/86	4,073	330	100	3,339	23	7,865	7,624
05/20/86	3,628	297	100			4,025	4,612
05/21/86	2,766	363	100			3,229	3,714
05/22/86	2,356	396	100			2,852	3,290
05/23/86	2,203	396	100			2,699	3,117
05/24/86	2,429	495	100			3,024	3,484
05/25/86	2,966	297	100			3,363	3,866
05/26/86	2,196	297	100			2,593	2,998
05/27/86	3,411	165	100	322		3,998	4,583
05/28/86	2,537	330	100			2,967	3,419
05/29/86	2,843	396	100			3,339	3,838
05/30/86	3,034	330	100			3,464	3,979
05/31/86	2,392	330	100			2,822	3,256
06/01/86	3,413	264	100			3,777	4,332
06/02/86	2,386	363	100			2,849	3,286

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
06/03/86	1,873	330	100			2,303	2,671
06/04/86	2,601	297	100			2,998	3,454
06/05/86	3,493	330	100	3,114		7,037	6,772
06/06/86	3,389	330	100			3,819	4,379
06/07/86	3,255	363	100	3,049		6,767	6,496
06/08/86	3,398	264	100			3,762	4,315
06/09/86	3,032	297	100			3,429	3,940
06/10/86	3,077	165	100	2,530		5,872	5,717
06/11/86	3,900	132	100	744		4,876	5,386
06/12/86	3,144	330	100			3,574	4,103
06/13/86	2,515	330	100			2,945	3,394
06/14/86	4,052	396	100			4,548	5,201
06/15/86	3,980	429	100			4,509	5,157
06/16/86	3,475	330	100	719		4,624	5,112
06/17/86	3,818	198	100			4,116	4,714
06/18/86	3,607	297	100			4,004	4,588
06/19/86	3,247	330	100			3,677	4,219
06/20/86	2,849	396	100			3,345	3,845
06/21/86	3,583	396	100			4,079	4,672
06/22/86	3,140	363	100			3,603	4,136
06/23/86	3,381	363	100			3,844	4,408
06/24/86	2,938	297	100			3,335	3,834
06/25/86	2,963	363	100			3,426	3,936
06/26/86	2,926	297	100			3,323	3,820
06/27/86	3,772	363	100	476		4,711	5,318
06/28/86	4,149	297	100			4,546	5,199
06/29/86	3,686	297	100			4,083	4,677
06/30/86	4,362	264	100	716		5,442	6,036
07/01/86	3,660	330	100			4,090	4,685
07/02/86	3,520	396	100			4,016	4,602
07/03/86	3,798	264	100			4,162	4,766
07/04/86	3,451	429	100			3,980	4,561
07/05/86	3,540	297	100			3,937	4,512
07/06/86	3,876	363	100			4,339	4,966
07/07/86	3,282	198	100			3,580	4,110

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
07/08/86	4,128	462	100	1,432		6,122	6,485
07/09/86	4,222	330	100	1,344	99	6,095	6,947
07/10/86	4,381	330	100			4,811	4,597
07/11/86	4,093	396	100	2,229		6,818	6,916
07/12/86	4,118	297	100	2,945		7,460	7,323
07/13/86	3,541	363	100			4,004	4,588
07/14/86	3,639	363	100			4,102	4,698
07/15/86	4,105	363	100	989		5,557	6,044
07/16/86	4,004	396	100			4,500	5,147
07/17/86	4,331	297	100			4,728	5,404
07/18/86	4,353	264	100			4,717	5,392
07/19/86	3,970	363	100			4,433	5,071
07/20/86	4,271	396	100			4,767	5,448
07/21/86	4,172	132	100			4,404	5,039
07/22/86	4,309	363	100			4,772	5,454
07/23/86	4,342	330	100			4,772	5,454
07/24/86	4,338	297	100			4,735	5,412
07/25/86	4,233	330	100	912		5,575	6,099
07/26/86	4,358	363	100			4,821	5,509
07/27/86	4,350	363	100			4,813	5,500
07/28/86	4,336	330	100	476		5,242	5,917
07/29/86	4,338	363	100			4,801	5,486
07/30/86	4,340	231	100			4,671	5,340
07/31/86	4,345	363	100	277		5,085	5,828
08/01/86	4,355	330	100			4,785	5,468
08/02/86	4,331	363	100			4,794	5,478
08/03/86	3,915	264	100			4,279	4,898
08/04/86	4,189	231	100			4,520	5,170
08/05/86	4,153	231	100			4,484	5,129
08/06/86	4,160	396	100			4,656	5,323
08/07/86	3,823	297	100			4,220	4,831
08/08/86	3,798	363	100			4,261	4,878
08/09/86	3,257	429	100			3,786	4,342
08/10/86	3,333	264	100			3,697	4,242
08/11/86	3,377	396	100			3,873	4,440

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
08/12/86	3,300	396	100			3,796	4,354
08/13/86	3,705	396	100			4,201	4,810
08/14/86	3,522	396	100			4,018	4,604
08/15/86	3,010	363	100			3,473	3,990
08/16/86	3,556	297	100			3,953	4,530
08/17/86	3,038	363	100			3,501	4,021
08/18/86	3,182	231	100			3,513	4,035
08/19/86	3,479	330	100			3,909	4,481
08/20/86	3,857	264	100			4,221	4,832
08/21/86	3,427	396	100			3,923	4,497
08/22/86	3,364	429	100			3,893	4,463
08/23/86	3,679	297	100			4,076	4,669
08/24/86	3,246	330	100			3,676	4,218
08/25/86	3,771	363	100			4,234	4,847
08/26/86	3,646	330	100	874		4,950	5,411
08/27/86	3,820	297	100			4,217	4,828
08/28/86	3,243	429	100			3,772	4,326
08/29/86	3,354	330	100			3,784	4,340
08/30/86	3,293	297	100			3,690	4,234
08/31/86	3,405	396	100			3,901	4,472
09/01/86	3,116	330	100			3,546	4,072
09/02/86	3,238	264	100			3,602	4,135
09/03/86	3,495	231	100			3,826	4,387
09/04/86	2,968	363	100			3,431	3,942
09/05/86	3,274	264	100			3,638	4,176
09/06/86	2,685	429	100			3,214	3,698
09/07/86	3,215	264	100			3,579	4,109
09/08/86	2,690	429	100			3,219	3,703
09/09/86	3,241	231	100			3,572	4,101
09/10/86	2,942	330	100			3,372	3,876
09/11/86	4,214	297	100	380		4,991	5,676
09/12/86	3,667	396	100			4,163	4,767
09/13/86	4,156	363	100			4,619	5,281
09/14/86	3,599	297	100			3,996	4,579
09/15/86	3,546	231	100			3,877	4,445

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
09/16/86	3,252	363	100			3,715	4,262
09/17/86	3,180	165	100			3,445	3,958
09/18/86	3,057	396	100			3,553	4,080
09/19/86	3,754	462	100			4,316	4,940
09/20/86	3,361	363	100			3,824	4,385
09/21/86	3,784	264	100	369		4,517	5,147
09/22/86	3,696	264	100	1,364		5,424	5,728
09/23/86	3,982	264	100	1,256		5,602	5,977
09/24/86	4,201	330	100	2,308		6,939	7,018
09/25/86	4,039	330	100	823		5,292	5,819
09/26/86	3,862	330	100	6,075	787	11,154	8,826
09/27/86	4,072	297	100	573	170	5,212	6,427
09/28/86	4,040	363	100	2,888		7,391	7,270
09/29/86	3,796	297	100	6,126	318	10,637	8,586
09/30/86	3,095	330	100	6,890		10,415	8,063
10/01/86	3,136	330	100	5,101		8,667	7,329
04/24/87	3,151	363	100			3,614	4,148
04/25/87	2,688	363	100			3,151	3,627
05/13/87	2,490	330	100			2,920	3,366
05/14/87	3,298	363	100			3,761	4,314
05/15/87	2,305	330	100			2,735	3,158
12/31/87	2,929	297	100			3,326	3,824
01/01/88	2,056	330	100			2,486	2,877
01/02/88	1,624	297	100			2,021	2,353
01/03/88	2,451	363	100			2,914	3,360
01/04/88	1,878	264	100			2,242	2,602
01/05/88	2,110	264	100			2,474	2,864
01/06/88	1,980	297	100			2,377	2,754
01/07/88	1,967	231	100			2,298	2,665
01/08/88	2,102	330	100			2,532	2,929
01/09/88	1,924	330	100			2,354	2,728
01/10/88	1,940	330	100			2,370	2,746
01/11/88	1,816	297	100			2,213	2,570
01/12/88	1,903	264	100			2,267	2,630
01/15/88	1,800	264	100			2,164	2,514

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
03/17/88	1,902	165	100			2,167	2,518
03/18/88	1,809	231	100			2,140	2,487
03/19/88	1,808	231	100			2,139	2,486
03/20/88	1,401	363	100			1,864	2,176
03/21/88	1,652	297	100			2,049	2,385
03/22/88	1,493	297	100			1,890	2,206
03/23/88	1,865	363	100			2,328	2,699
03/24/88	2,027	330	100	654		3,111	3,436
03/25/88	1,939	396	100	162		2,597	3,075
03/26/88	2,025	198	100			2,323	2,694
03/27/88	2,029	264	100			2,393	2,772
03/28/88	3,734	363	100	1,092		5,289	5,697
03/29/88	4,298	297	100	1,069		5,764	6,242
03/30/88	4,331	264	100	2,201		6,896	7,017
03/31/88	4,339	330	100			4,769	5,450
04/01/88	4,143	264	100			4,507	5,155
04/02/88	3,789	198	100	950		5,037	5,476
04/03/88	3,209	330	100			3,639	4,177
04/04/88	2,969	396	100			3,465	3,980
04/05/88	2,981	297	100	416		3,794	4,311
04/06/88	4,171	198	100	1,879		6,348	6,542
04/07/88	4,213	363	100	825		5,501	6,054
04/08/88	4,243	396	100			4,739	5,416
04/09/88	3,544	297	100			3,941	4,517
04/10/88	2,884	330	100			3,314	3,810
04/11/88	2,285	198	100			2,583	2,986
04/12/88	2,650	297	100			3,047	3,509
04/13/88	2,038	231	100			2,369	2,745
04/14/88	2,324	330	100			2,754	3,179
04/15/88	1,766	330	100			2,196	2,550
04/16/88	1,737	396	100			2,233	2,592
04/17/88	1,970	264	100			2,334	2,706
04/18/88	1,847	297	100			2,244	2,604
04/19/88	1,567	330	100			1,997	2,326
04/20/88	1,856	297	100			2,253	2,615

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
04/21/88	1,862	396	100			2,358	2,733
04/22/88	1,993	231	100			2,324	2,695
04/23/88	2,439	396	100			2,935	3,383
04/24/88	1,802	396	100			2,298	2,665
04/25/88	2,053	165	100			2,318	2,688
04/26/88	2,347	363	100			2,810	3,242
04/27/88	2,192	396	100			2,688	3,105
04/28/88	2,030	429	100			2,559	2,959
04/29/88	1,728	330	100			2,158	2,508
04/30/88	1,897	330	100			2,327	2,698
05/01/88	1,813	330	100			2,243	2,603
05/02/88	1,702	363	100			2,165	2,515
05/03/88	1,740	363	100			2,203	2,558
05/04/88	1,575	396	100			2,071	2,409
05/05/88	1,808	330	100			2,238	2,598
05/06/88	2,007	231	100			2,338	2,710
05/07/88	1,957	330	100			2,387	2,766
05/08/88	2,371	330	100			2,801	3,232
05/09/88	2,496	297	100			2,893	3,336
05/10/88	1,601	363	100			2,064	2,402
05/11/88	1,623	297	100			2,020	2,352
05/12/88	2,028	363	100			2,491	2,883
05/13/88	2,046	264	100			2,410	2,792
05/14/88	1,701	429	100			2,230	2,589
05/15/88	2,352	363	100			2,815	3,248
05/16/88	2,013	330	100			2,443	2,829
05/17/88	1,761	495	100			2,356	2,731
05/18/88	1,909	231	100			2,240	2,600
05/19/88	1,598	363	100			2,061	2,398
05/20/88	1,700	264	100			2,064	2,402
05/21/88	1,809	396	100			2,305	2,673
05/22/88	1,659	462	100			2,221	2,578
05/23/88	2,843	198	100	212		3,353	3,905
05/24/88	3,519	396	100			4,015	4,600
11/03/88	1,415	330	100			1,845	2,155

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
11/04/88	3,278	297	100	1,133		4,808	5,137
11/05/88	2,734	363	100			3,197	3,678
11/06/88	3,044	330	100			3,474	3,991
11/07/88	2,072	264	100			2,436	2,821
11/08/88	1,905	396	100			2,401	2,781
11/09/88	2,981	363	100	2,046		5,490	5,501
11/10/88	3,664	297	100	2,415		6,476	6,449
11/11/88	4,219	429	100			4,748	5,426
11/12/88	3,807	396	100			4,303	4,925
11/13/88	4,061	198	100			4,359	4,988
11/14/88	2,460	66	100			2,626	3,035
11/15/88	3,342	99	100	3,766		7,307	6,787
11/16/88	4,107	132	100	2,134		6,473	6,570
11/17/88	3,383	99	100			3,582	4,112
01/31/89	1,937	231	100			2,268	2,632
02/01/89	1,605	363	100			2,068	2,406
02/02/89	1,662	264	100			2,026	2,359
02/03/89	1,758	198	100			2,056	2,392
06/12/89	2,117	330	100	1,261		3,808	3,953
06/13/89	2,117	330	100	1,261		3,808	3,953
06/14/89	2,166	297	100	772		3,335	3,636
08/22/89	3,619	363	100			4,082	4,676
08/23/89	3,180	264	100			3,544	4,070
09/26/89	2,022	330	100			2,452	2,839
09/27/89	1,872	462	100			2,434	2,818
09/28/89	1,872	462	100			2,434	2,818
09/29/89	1,440	330	100			1,870	2,183
09/30/89	1,494	462	100			2,056	2,392
10/01/89	1,946	528	100			2,574	2,976
10/02/89	1,711	429	100			2,240	2,600
10/03/89	2,234	264	100			2,598	3,003
10/04/89	1,855	396	100			2,351	2,725
10/05/89	2,105	396	100			2,601	3,007
10/06/89	2,308	330	100			2,738	3,161
10/10/89	1,876	363	100			2,339	2,712

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
10/11/89	1,686	396	100			2,182	2,534
10/12/89	1,748	264	100			2,112	2,456
10/13/89	2,013	363	100			2,476	2,866
11/15/89	3,537	231	100	3,632		7,500	7,064
11/16/89	4,313	99	100			4,512	5,160
11/17/89	2,520	330	100			2,950	3,400
11/18/89	2,628	264	100			2,992	3,447
11/19/89	2,200	297	100			2,597	3,002
11/20/89	1,896	297	100			2,293	2,660
11/21/89	1,588	330	100			2,018	2,350
03/16/90	2,951	198	100			3,249	3,737
03/17/90	2,770	264	100			3,134	3,607
03/18/90	2,445	297	100			2,842	3,278
03/19/90	2,552	132	100			2,784	3,213
04/29/90	1,406	363	100			1,869	2,182
04/30/90	1,820	330	100			2,250	2,611
05/01/90	1,526	264	100			1,890	2,206
05/04/90	3,779	297	100	5,689	427	10,292	8,411
05/05/90	3,670	495	100			4,265	4,882
05/06/90	2,948	363	100			3,411	3,920
05/07/90	2,048	297	100			2,445	2,831
05/08/90	2,364	363	100			2,827	3,262
05/09/90	3,102	264	100	6,322	3,117	12,905	8,755
05/10/90	3,812	66	100	20,217	10,795	34,990	17,870
05/11/90	4,008	165	100	16,622	2,888	23,783	14,083
05/12/90	4,000	297	100	10,563	432	15,392	10,787
05/13/90	4,204	396	100	5,986		10,686	8,993
05/14/90	4,199	330	100	5,127		9,756	8,539
05/15/90	4,102	363	100	3,786		8,351	7,955
05/16/90	3,225	363	100	3,056		6,744	6,467
05/17/90	3,616	396	100			4,112	4,710
05/18/90	2,468	495	100			3,063	3,527
05/19/90	3,770	462	100	2,177		6,509	6,591
05/20/90	3,195	396	100			3,691	4,235
05/21/90	2,681	363	100			3,144	3,619

Appendix 2: Listing of discharges estimated for days when the acoustic velocity meter was inoperative--Continued

Date	Discharge, in cubic feet per second						
	Turbine	Lockage	Leakage	Sluice gate	Contolling works	MWRD total	USGS estimated
05/22/90	2,423	297	100			2,820	3,254
05/23/90	2,269	231	100			2,600	3,006
05/24/90	2,080	363	100			2,543	2,941
05/25/90	3,735	396	100			4,231	4,844
05/26/90	3,468	462	100			4,030	4,617
05/27/90	3,010	462	100			3,572	4,101
05/28/90	1,945	429	100			2,474	2,864
05/29/90	1,961	198	100			2,259	2,621
05/30/90	1,927	297	100			2,324	2,695
06/14/90	3,290	396	100	363		4,149	4,735
03/27/91	3,998	264	100	3,465		7,827	7,506
04/20/91	3,465	363	100			3,928	4,502
04/21/91	2,790	429	100			3,319	3,816
04/22/91	1,145	297	100			1,542	1,813
04/23/91	2,175	231	100	3,152		5,658	5,200
04/24/91	3,216	198	100			3,514	4,036
05/31/91	2,070	198	100	3,846		6,214	5,520
06/01/91	2,101	429	100	1,888		4,518	4,475
06/02/91	2,122	330	100	333		2,885	3,324
06/03/91	2,020	330	100	554		3,004	3,360