TECHNICAL PUBLICATION
EMA #416

RATING ANALYSIS FOR PUMP STATION S13

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May, 2004

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EXECUTIVE SUMMARY

This document summarizes the results of rating analysis, model development and calibration for flow through the pumps at S13. S13 is a three unit pump station located in Canal 11(South New River Canal) about 300 feet west of U.S. Highway 441 and 5.5 miles southwest of Fort Lauderdale, Florida.

There are eighteen field flow measurements for pump station S13, which include sixteen measurements with headwater less than tailwater and two with headwater higher than tailwater. All of the measurements are used for this rating analysis. The rating analysis results show that the relative errors in discharge vary from -35.1% to 15.7% and the average relative error is -6.0% for the existing rating equation. The results show also that flow data accuracy can be further improved by using the new rating equation developed, calibrated, and presented here.

The new flow rating equation was developed based on the manufacturer's pump performance curves and the pump affinity laws, and calibrated using the available field measurements. The average relative error, based on sixteen measurements, is -0.8%, with the relative errors ranging from -16.3% to 14.9% for the new rating equation. The new rating has 44% of calculated flows within 5% of the measured discharges, 69% within 10%, and 94% within 15%, while the existing rating equation has 13 % of calculated flows within 5% of the measured discharges, 50% within 10%, and 56% within 15%. The new rating equation is an improvement over the existing one. Two measurements with headwater more than tailwater show results consistent with the concept that pump discharge is higher when assisted by gravity.

An assessment of impact of the new flow rating equation on historical data was performed using breakpoint flows with daily means obtained using IVG (a software application developed in-house). The average percent change between the existing and the new flow rating equations is -7.89% for the period from January 1996 through January 2004.

The improvement in flow data accuracy is 7.8% for the new rating equation. It is recommended that the existing rating equation be replaced by the new one. It is further recommended that two to three additional stream flow measurements be used from time to time to verify the performance of the new rating equation. If the new rating equation can not be verified, then seven to twelve additional stream flow measurements should be made to recalibrate the flow rating equation.

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LIST OF ABBREVIATIONS AND ACRONYMS

DBHYDRO	Hydrometeorologic and Water Quality Database
IVG	Interval Value Generator
OMD	Operations and Maintenance Department
Qmeas	Database table containing measured flow data
Qmr	Program that ranks errors at a station per range of operation
Qverify	Program that compares measured and computed discharges per station
SQL	Structured Query Language
STA	Stormwater Treatment Area

ACKNOWLEDGEMENT

The authors would like to acknowledge Robb Startzman, Garth Redfield, Emile Damisse, and Scott Huebner for their review of the draft and valuable comments. Carol Goff and Robin Campbell are gratefully acknowledged for assistance in coordinating the review and production of this document.

RATING ANALYSIS FOR PUMP STATION S13

1. Introduction

The structure S13 is a combination of a pumping station and a gated spillway. S13 is located in Canal 11(South New River Canal) about 300 feet west of U.S. Highway 441 and 5.5 miles southwest of Fort Lauderdale (Figure 1). The pump station is equipped with three vertical propeller pumps each having a rated capacity of 180 cfs at a 4 ft static head. The design engine speed was increased from 1200 to 1625 rpm with change in gear ratio to maintain design pump speed when engines were replaced on February 1995 (OMD 2002).

The purpose of the structure is to release flood runoff from, prevent overdrainage of, and prevent salt water intrusion into the agricultural area served by Canal 11 west of the structure. The pumping units in the structure are used for discharging surplus water from the agricultural area west of the structure. It is intended to keep the water level in the C-11 canal as close to the optimum elevation of 2.2 ft above mean sea level as possible.

Pump operation takes place when the headwater elevation is over 2.5 ft above mean sea level and the tailwater elevation is less than 8 ft above mean sea level. The headwater elevation varies from 2.2 ft to 2.5 ft and the tailwater elevation varies from 6.2 ft to 6.5 ft. The design discharge for the pumps is 540 cfs (Imru, 1999).

The annual flow records of structure S13 consist of flows through the spillway and those through the pumps. The responsibility of flow monitoring through the spillway and through the pumps is divided between two agencies. Discharge computation through the spillway is handled by USGS while the South Florida Water Management District (District) computes flow through the pumps.

This report summarizes the flow rating analysis performed for pumps at S13. Section 2 outlines the objective and scope for the rating analysis at S13. Stream flow measurements and existing flow rating equation are described in Sections 3 and 4 respectively. Sections 5 and 6 discuss evaluation of the existing flow equation and determination of need for improvement. Development of a new flow rating equation is discussed in Section 7 and calibration of the new flow rating equation is discussed in Section 8. Section 9 presents the results of impact analysis. Sections 10 and 11 provide conclusion and recommendation respectively.

2. Objective and Scope

The objective of this discharge rating analysis is to evaluate the existing rating equation and develop a new rating equation that can improve flow calculations and reduce relative errors of pump flow data. Equations for estimating flow at pump stations in the District are classified into eight cases (Case 1 through Case 8). The existing flow rating equation for S13 is classified as Case 7. The new rating equation (Case 8) is developed based on the manufacturer's pump performance curves and the pump affinity laws, and calibrated using flow data obtained through streamgauging. This report presents estimation of flow computation errors in relation to field measurements for the existing equation as well as for the new rating equation.

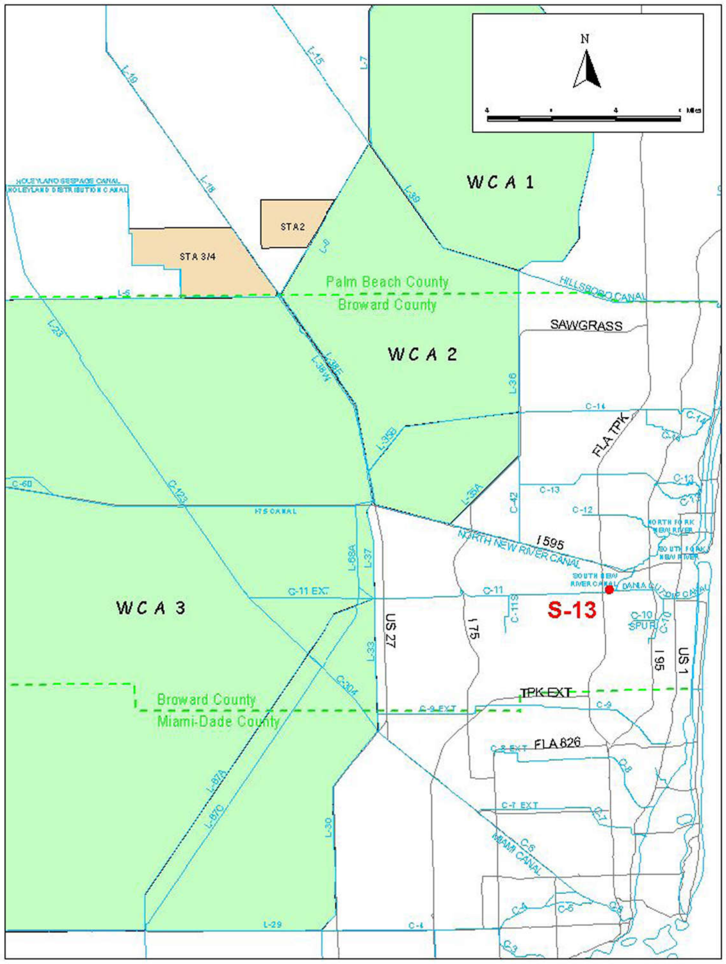

Figure 1. Location map for pump station S13

3. Stream Flow Measurements

3.1 Available Measurements

There were eighteen stream flow measurements for this station in the streamgauging records at the time of this analysis. The available measurements for pump station S13 were obtained by running structured query language (SQL) scripts shown in Appendix A and all the records for S13 are shown in Appendix B. The available measurements were divided into two groups based on the time the engine was replaced (February 1995). Group 1 includes five measurements prior to 1995 and Group 2 includes thirteen measurements after 1995. The pump station S13 contains three variable-speed pumps and the measured discharge per unit was determined based on the total number of pumps operating at the time of each measurement. The head differential for each measurement was calculated based on the headwater and tailwater elevations. Figure 2 shows the stream flow measurements at various head and engine speed combinations for all units of S13. As shown in Figure 2, no measurement is available at design engine speed 1625 rpm at the time of this analysis.

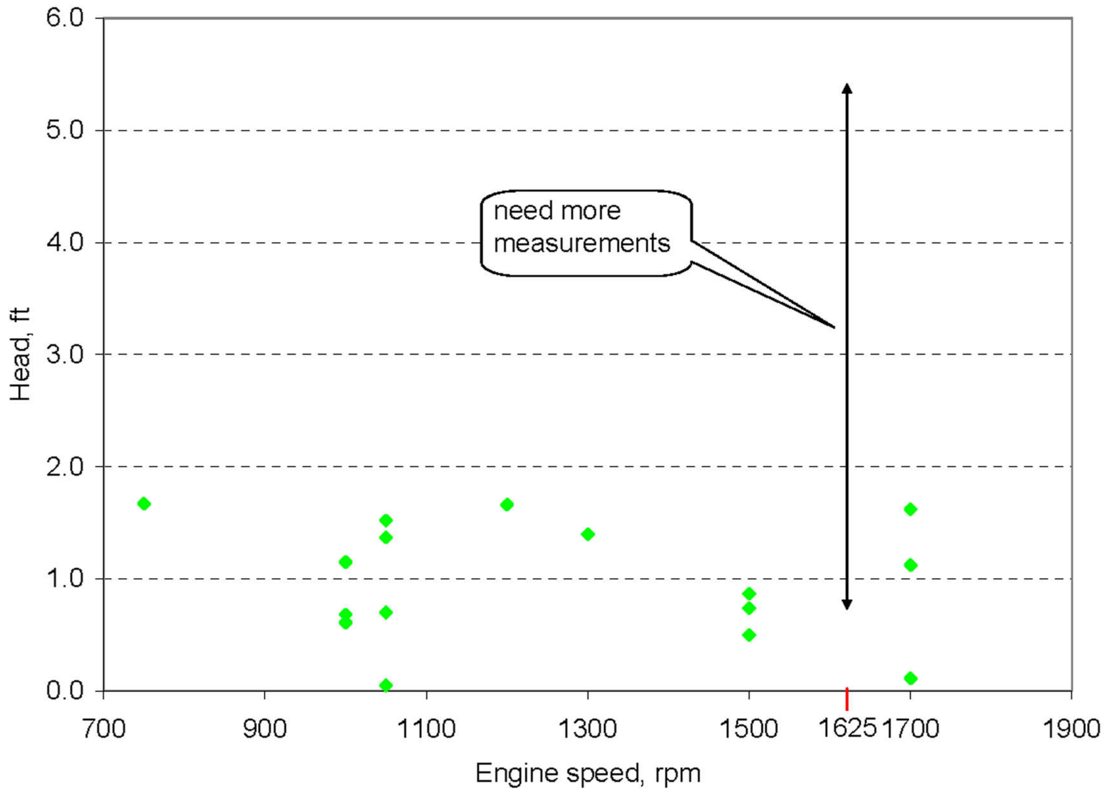

Figure 2. Flow measurements at various head and engine speed combinations for S13

3.2 Additional Measurements Required

The design engine speed was increased from 1200 to 1625 rpm with change in gear ratio to maintain design pump speed when engines were replaced on February 1995. The maximum and minimum values for headwater and tailwater elevations were obtained from the hydrometeorologic and water quality database (DBHYDRO). The possible maximum and minimum head differentials for S13 were estimated and summarized in Table 1. The head differentials were categorized into three different ranges (low, medium, and high). The number of measurements required per range of operation for S13 was obtained by running Qmr (a program that ranks errors at a station per range of operation) and the results are shown in Table 2. The additional measurements needed are shown in Figure 2. Table 3 is the summary of the available and required additional measurements.

Table 1. Maximum and minimum stages for pump station S13

Station	Stage	Maximum		Minimum	
		Value	Date	Value	Date
S13_P	Headwater	4.66	16-Aug-99	0	4-Feb-98
	Tailwater	4.26	26-Oct-01	0	28-Feb-96
	Head differentials	4.26		0	

Table 2. Streamgauging needs for pump station S13

Range of Head Differential, ft	Range of Operation, rpm (RPM)		
	1000≤RPM≤1267	1267<RPM<1533	1533≤RPM≤1800
0.0≤DIFF≤2.0	0	0	0
2.0<DIFF≤4.0	5*	5*	5*
4.0<DIFF≤6.0	5*	5*	5*

Note: * first priority

Table 3. Available and required additional measurements for pumps at S13

Pump Station	Design Engine Speed (rpm)	Range of Head Differential (ft)	Measurements		
			RPM	Available	Required
S13_P	1625	0.0≤DIFF≤2.0	1000≤RPM≤1700	18	1
		2.0<DIFF≤4.0	1625	0	5
		4.0<DIFF≤6.0	1625	0	5

4. Existing Flow Rating Equation

Pumps at S13 are, for flow calculation purposes, classified as Case 7. The brief descriptions provided here were taken from Discharge Rating for S13_P Pump Station (Imru, 1999). In Case 7, the flow equations were developed from pump affinity laws and are given by:

$$Q = \left(\frac{N}{N_R}\right)\left[C_1\sqrt{H} + C_3\right] \text{ if HW} < \text{TW} \tag{1}$$

and

$$Q = \left(\frac{N}{N_R}\right)\left[C_2\sqrt{H} + C_4\right] \text{ if HW} \geq \text{TW} \tag{2}$$

where, Q is the discharge in cfs; N_R is the rated rpm of the engine; N is the engine speed; C_1 through C_4 are regression coefficients; HW and TW are headwater and tailwater elevations in ft, respectively; and H is the absolute head differential, i.e., H = |HW-TW|. N and N_R need to refer to the same source (pump impeller or engine speed). The flow coefficients for pumps at S13 are taken from Atlas of Flow Computations at District Hydraulic Structures (Ansar et al., 2003) and given in Table 4.

Table 4. Flow coefficients for pumps at S13 in Case 7 for the existing rating equations

Station	Units	C_1	C_2	C_3	C_4	N_R
S13_P	1-3	-15.0	0.43	183.0	183.0	1600

Table 5 shows discharges calculated using the existing flow rating equation based on the headwater, tailwater, and engine speed obtained from the streamgauging database (Qmeas) table. The last column in Table 5 indicates the estimated discharges (Q) from the existing rating equation for S13 corresponding to the available streamgauging data.

Table 5. Existing flow estimation at S13 using input data from streamgauging records

DATE	TIME	HW	TW	H	N	$Q_{per\ unit}$	# of pump	Q_{total} computed
		ft	ft	ft	rpm	cfs		cfs
5-Apr-91	14:34	0.54	1.24	0.70	1050	112	3	336
2-Oct-91	14:25	0.06	1.73	1.67	750	77	3	230
17-Oct-91	13:18	1.13	1.18	0.05	1050	118	2	236
24-Oct-91	13:42	0.52	2.04	1.52	1050	108	2	216
7-Oct-93	12:30	1.10	2.25	1.15	1000	104	3	313
10-Jun-96	11:37	1.64	0.86	0.78	1600	183	3	550
10-Sep-96	13:04	11.24	11.35	0.11	1700	189	3	567
10-Sep-96	13:49	11.24	11.17	0.07	1700	195	2	389
7-Oct-96	11:27	0.86	1.60	0.74	1500	159	3	478
15-Jun-97	17:05	0.11	1.77	1.66	1200	123	3	368
15-Jun-97	18:00	0.20	1.82	1.62	1700	174	3	522
7-Nov-98	9:11	0.50	1.62	1.12	1700	178	3	533
7-Nov-98	10:25	0.62	2.02	1.40	1300	134	3	403
7-Nov-98	11:33	0.96	2.33	1.37	1050	109	3	326
23-Jun-99	8:51	0.57	1.44	0.87	1500	158	3	475
23-Jun-99	9:54	0.49	1.10	0.61	1000	107	3	321
23-Jun-99	10:59	0.41	0.91	0.50	1500	162	3	485
26-Aug-99	14:02	0.32	1.00	0.68	1000	107	3	320

5. Evaluation of Existing Flow Equation

The existing flow rating equation for pump station S13 was developed based on the energy principle and the pump affinity laws (Imru, 1999) and equations (1) and (2) are currently used in the FLOW program. Though the estimated flow values are reasonable, a plot of the existing equation shows a concave up curve. The manufacturer's performance curves are concave down (Figure3). This was a motivation to re-evaluate the existing rating equation of the pumps at S13.

There were eighteen stream flow measurements for this station in the streamgauging records. All of these data points are considered in the rating analysis for the existing flow equation. Based on the available measurements, the relative errors in discharge were obtained by running Qverify (a program that compares measured and computed discharges per station) for the existing flow rating equation and the results are shown in Table 6.

In Table 6, the individual relative errors between measured and computed flow are shown in the last column. A negative relative error value indicates that the Flow program underestimated the actual discharge. Conversely, a positive relative error value indicates that the estimate was greater than the measured discharge. The relative errors (Table 6) vary from -35.07% to 15.72% and the average relative error is -4.75% for all the measurements. The absolute relative errors for S13 per range of operation were obtained by running Qmr and the results are shown in Table 7. The evaluation results from the comparison between measured and computed discharges and the results of errors per range of operation are used to determine whether the existing rating equation for pump station S13 can be improved or not.

Table 6. Comparison of measured and computed discharges for the existing rating equation

No.	Date	Time	Head Water	Tail Water	Q Measured	Q Computed	Relative Error
1	5-Apr-91	14:34	0.54	1.24	468	336	-28.30%
2	2-Oct-91	14:25	0.06	1.73	329	230	-30.07%
3	17-Oct-91	13:18	1.13	1.18	325	240	-26.10%
4	24-Oct-91	13:42	0.52	2.04	291	216	-25.80%
5	7-Oct-93	12:30	1.10	2.25	482	313	-35.07%
6	10-Jun-96	11:37	1.64	0.86	537	550	2.45%
7	10-Sep-96	13:04	11.24	11.35	540	567	5.08%
8	10-Sep-96	13:49	11.24	11.17	366	389	6.32%
9	7-Oct-96	11:27	0.86	1.60	512	478	-6.56%
10	15-Jun-97	17:05	0.11	1.77	350	368	5.22%
11	15-Jun-97	18:00	0.20	1.82	507	522	3.05%
12	7-Nov-98	9:11	0.50	1.62	506	533	5.28%
13	7-Nov-98	10:25	0.62	2.02	392	403	2.76%
14	7-Nov-98	11:33	0.96	2.33	298	326	9.30%
15	23-Jun-99	8:51	0.57	1.44	443	475	7.30%
16	23-Jun-99	9:54	0.49	1.10	278	321	15.52%
17	23-Jun-99	10:59	0.41	0.91	419	485	15.72%
18	26-Aug-99	14:02	0.32	1.00	362	320	-11.62%
Minimum Relative Error Value:							-35.07%
Maximum Relative Error Value:							15.72%
Average of relative errors							-4.75%
Average of absolute values of relative errors							13.42%
95% Lower Confidence Interval for the Mean:							-11.66%
95% Upper Confidence Interval for the Mean:							2.16%
Distribution of Absolute Relative Errors:							
Percentage of data with Absolute Relative Error <= 5% is: (Rating is very good)							16.67%
Percentage of data with 5% < Absolute Relative Error <= 10% is: (Rating is good)							38.89%
Percentage of data with 10% < Absolute Relative Error <= 15% is: (Rating is fair)							5.56%
Percentage of data with Absolute Relative Error > 15% is: (Rating is poor)							38.89%
Number of Records Retrieved from Database:							18
Number of Records with Valid Flow Estimates:							18

Table 7. Absolute error per range of operation for S13

Range of Head Differential, ft (DIFF)	Range of Operation, rpm (RPM)				
	1000≤RPM≤1267	1267<RPM<1533	1533≤RPM≤1800	Abs Error (%)	
				Mean	Max
0.0≤DIFF≤2.0	22.51	6.71	4.44	14.45	55.62
2.0<DIFF≤4.0	–	–	–	–	–
4.0<DIFF≤6.0	–	–	–	–	–
Mean	22.51	6.71	4.44	14.45	–

6. Determination of Need for Improvement

Based on the existing stream flow measurements, the relative errors in discharge were obtained using Qverify for the existing rating equation (Table 6). Data verification results are reported in terms of relative errors that help to categorize the correlation of measured data to computed data as excellent, good, fair or poor. The rating is classified as "excellent" when about 95 percent of the predicted flow rates are within 5 percent of the measured discharges, "good" if the flow data are within 10 percent, "fair" if they are within 15 percent and "poor" when they are not within 15 percent (Akpoji et al, 2003).

As shown in Table 6, the average of absolute relative errors (13.42%) is more than 10% and the percentage of data with absolute relative errors within 15% is 61.11% (less than 95%); The Qmr results in Table 7 show that the absolute errors are higher at the lower range of head differential (between 0.0 and 2.0 ft) and the lower engine speed. Overall, the results from Qverify and Qmr show that the existing rating has room for improvement. The development of a new rating equation will be essential for better flow estimation accuracy.

An attempt was made to determine discharge rating coefficients in case 8 for the pumps at S13 by Engineering & Applied Science, Inc. (EAS, 2002). The EAS rating equation was given by:

$$Q = 1913.35\left[\frac{N}{N_0}\right] - 1786.85H^{0.01}\left[\frac{N_0}{N}\right]^{-0.98} \tag{3}$$

The following observations suggest that a reliable discharge coefficient was not determined.

1. The mean absolute relative error is 28.3% (EAS, 2002).
2. The pump performance curve was not included in the EAS rating analysis report; knowledge of the pump curve can help to define the shape of the rating.
3. The design engine speed was increased from 1200 to 1625 rpm on February 1995. They made mistakes in the data analysis by using wrong design engine speed.
4. The value of coefficient A in equation (3) is 1913.35 and it is too high relative to the design flow (180 cfs).
5. The value of exponent C in equation (3) is 0.01, which is less than 1. This is in conflict with the pump curve showing concave down (Damisse, 2000).

The motivation to revise the flow rating analysis for the pumps at S13 was based on the points listed above.

7. Development of a New Flow Rating Equation

The pump characteristic curves supplied by the manufacturer were used in conjunction with the principles of energy and mass conservation, and the pump affinity laws to develop a model for estimating flow through the pumps at S13. Figure 3 shows the head-discharge relationship for flows through the pumps at S13 under laboratory conditions at design engine speed. The performance curves are parabolic with concave down suggesting that a polynomial function with a power higher than one may be appropriate to compute flow for pumps at S13.

From the energy conservation principle, the velocity is a function of the head differential. Discharge through a constant cross section (such as a pump flow section), which is directly proportional to velocity is a function of the head. On the basis of this concept Equation (4) is valid for all Q and H values for the rated pump speed (Imru and Wang, 2003). The absolute value of the hydraulic head differential (H) is used in all subsequent equations.

$$Q_o = f(H) = A + B\,H_0^{\,C} \tag{4}$$

In Equation (4), Q_o is the discharge for a reference pump speed; H_0 is head differential that corresponds to Q_o. A and B are constant coefficients and C is a constant exponent.

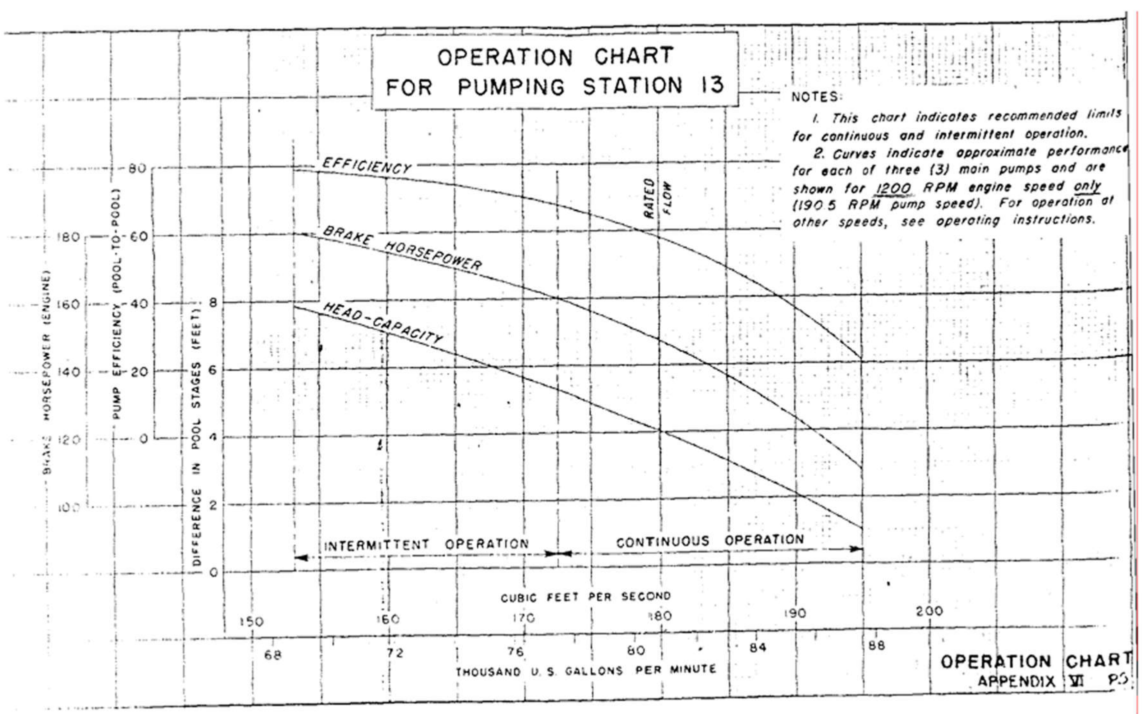

Figure 3. Performance curves for pumps at S13

The flow rate changes proportionally according to the pump affinity laws when the pump speed varies. The pump affinity laws assume no change in efficiency when engine speed changes and the relation between the change in discharge and the change in pump speed is given by

$$\frac{Q}{Q_0} = \frac{N}{N_0} \tag{5}$$

Substituting Equation (4) into Equation (5) and rearranging, we obtain Equation (6).

$$Q = \frac{N}{N_0}(A + B H_0^{\,C}) \tag{6}$$

H_0 can be written in terms of H using the following relation of the pump affinity laws.

$$H_0 = \left[\frac{N_0}{N}\right]^2 H \tag{7}$$

Substituting Equation (7) in Equation (6) and rearranging, we obtain Equation (8).

$$Q = A\left[\frac{N}{N_0}\right] + BH^C\left[\frac{N_0}{N}\right]^{2C-1} \tag{8}$$

where, Q is the discharge at head H; N_0 is the rated engine speed; N is the field engine speed.

Equation (8) presents a model based on physical laws that can be used to estimate flow through variable speed pumps. This equation describes the relationship between discharge, head differential, and engine speed. Equation (8) will be calibrated to estimate flow for S13.

8. Calibration of the New Flow Rating Equation

The available measurements and pump performance curves are used to perform the rating calibration. The discharges at the rated engine speed were obtained from the field data using the pump affinity laws. The regression coefficients of Equation (4) are determined based on the least-squares method (Davis, 1986). According to the least-squares method, the deviation of the estimate from the measurement is $((A + BH_0^{\,C}) - Q_0)$, and the goal becomes one of finding a method such that

$$F = \sum_{i=1}^{n}\left(\left(A + BH_0^{\,C}\right) - Q_0\right)^2 = \text{ minimum} \tag{9}$$

The expanded form of the above equation is given by

$$F = \sum_{i=1}^{n}\left(Q_0^{\,2} - 2AQ_0 - 2BH_0^{\,C}Q_0 + A^2 + 2ABH_0^{\,C} + B^2H_0^{\,2C}\right) \tag{10}$$

Mathematically F is minimized by setting its partial derivatives with respect to coefficients A, B, and C equal to zero. The partial derivatives were estimated individually, however, the results show that the three partial derivatives are equivalent and given below

$$\frac{\partial F}{\partial A} = \frac{\partial F}{\partial B} = \frac{\partial F}{\partial C} = \sum_{i=1}^{n} \left(2A + 2BH_0^{\ C} - 2Q_0 \right) = 0 \tag{11}$$

$$B = \frac{\sum_{i=1}^{n} Q_0 - nA}{\sum_{i=1}^{n} H_0^{\ C}} \tag{12}$$

where n is the total number of measurements.

A starting estimate for coefficient A would be: $A = \sum Q_0 / n$. For a parabolic equation, the coefficient A is between the design discharge and the discharge at zero lift. According to Damisse (2000) the coefficient C is more than one. Equation (12) can help to iteratively solve B for the given values of A and C. An iterative simulation helps to determine the optimum values of coefficients A, B, and C for the new rating equation.

The available stream flow measurements for S13 are tabulated in Appendix B and all the available measurements were grouped into two based on the time the engines were replaced (February 1995). Group 1 includes five measurements prior to 1995 and Group 2 includes thirteen measurements after 1995. In this case, only thirteen measurements in Group 2 were considered for calibration. In Group 2, there are eleven measurements with headwater lower than tailwater and two measurements with headwater higher than tailwater. For pumps at S13, the eleven measurements in Group 2 were used to calibrate the new rating equation (4). The rated flows (Q_0) and heads (H_0) at the design engine speed are shown in Table 8.

Table 8. Rated flow and head at S13 for the selected measurements

No.	DATE	TIME	HW	TW	Head	N	Q per unit	$Q_0=(N_0/N)Q$	$H_0=H(N_0/N)^2$
1	10-Sep-96	13:04	11.24	11.35	0.1	1700	180.0	172.1	0.10
2	7-Oct-96	11:27	0.86	1.6	0.7	1500	170.7	184.9	0.87
3	15-Jun-97	17:05	0.11	1.77	1.7	1200	116.7	158.0	3.04
4	15-Jun-97	18:00	0.2	1.82	1.6	1700	169.0	161.5	1.48
5	7-Nov-98	9:11	0.5	1.62	1.1	1700	168.7	161.2	1.02
6	7-Nov-98	10:25	0.62	2.02	1.4	1300	130.7	163.3	2.19
7	7-Nov-98	11:33	0.96	2.33	1.4	1050	99.3	153.7	3.28
8	23-Jun-99	8:51	0.57	1.44	0.9	1500	147.7	160.0	1.02
9	23-Jun-99	9:54	0.49	1.10	0.6	1000	92.7	150.6	1.61
10	23-Jun-99	10:59	0.41	0.91	0.5	1500	139.7	151.3	0.59
11	26-Aug-99	14:02	0.32	1.0	0.7	1000	120.7	196.1	1.80

Table 9 shows the values of coefficients and exponents determined from regression analysis for the new rating equation for the new engines (after February 1995). For engines prior to 1995, the values of coefficients and exponents of the new rating equation are tabulated in Table 10. As shown in Tables 9 and 10, the values of the coefficient B are negative as long as the headwater elevation is lower than the tailwater elevation and can be positive when headwater stage is higher than the tailwater stage. This is consistent with the concept that pump discharge is higher when assisted by gravity and lower when working against a positive static head (Imru and Wang, 2003). Two measurements with headwater higher than tailwater give flows consistent with the concept that pump discharge is higher when assisted by gravity. Equation (13) was used with a positive B value (B= 4.4 instead of -4.4). The absolute relative errors for these two measurements are within 2% using the new rating equation. However, the concept needs further investigation with more field flow measurements when the tailwater is lower than the headwater. Since there are not enough field flow measurements for this condition, it is considered better to disregard the effect of head differential when the headwater is higher than the tailwater.

For pumps at S13, the rated capacity is 180 cfs while the value of the coefficient A is 176 cfs for the new rating equation. The following two points are worth noting.

1. The average of the rated discharge is 164 cfs for selected measurements at S13.
2. The maximum measured discharge per unit is 180 cfs at engine speed 1700 rpm at head 0.1 ft. The value of coefficient A is the discharge at zero lift for the design engine speed (1625 rpm).

Table 9. New pump equation coefficients and exponents for the new engines after 1995

Unit	N_0	Headwater < Tailwater		
		A	B	C
1	1625	176	-4.4	1.3
2	1625	176	-4.4	1.3
3	1625	176	-4.4	1.3

Table 10. New pump equation coefficients and exponents for the old engines prior to 1995

Unit	N_0	Headwater < Tailwater		
		A	B	C
1	1200	176	-4.4	1.3
2	1200	176	-4.4	1.3
3	1200	176	-4.4	1.3

Equation (13) presents the new flow rating equation developed to estimate flow through each diesel pump at S13.

$$Q = 176\left[\frac{N}{N_0}\right] - 4.4H^{1.3}\left[\frac{N_0}{N}\right]^{1.6} \tag{13}$$

where Q is the discharge at head H for field engine speed N.

Table 11 shows the measured discharges and discharges computed using the new rating equation for S13. In Table 11, one of the sixteen measurements (on October 2, 1991) gives a high relative error (-16.3%). Probably it is because this measurement was done at a speed of 750 rpm, which is very low relative to the design engine speed. The no flow engine speed for S13 is 700 rpm (DBHYDRO), which is not much lower than 750 rpm.

Table 11. Comparison of measured and computed discharges for the new rating equation

No.	DATE	TIME	HW	TW	N	N_0	Q measured	Q computed new	Relative error	Abs. error
			(ft)	(ft)	(rpm)	(rpm)	(cfs)	(cfs)		
1	5-Apr-91	14:34	0.54	1.24	1050	1200	156	151	-3.5%	3.5%
2	2-Oct-91	14:25	0.06	1.73	750	1200	110	92	-16.3%	16.3%
3	17-Oct-91	13:18	1.13	1.18	1050	1200	163	154	-5.3%	5.3%
4	24-Oct-91	13:42	0.52	2.04	1050	1200	146	145	-0.6%	0.6%
5	7-Oct-93	12:30	1.10	2.25	1000	1200	161	140	-13.1%	13.1%
6	10-Sep-96	13:04	11.24	11.35	1700	1625	180	184	2.2%	2.2%
7	7-Oct-96	11:27	0.86	1.60	1500	1625	171	159	-6.8%	6.8%
8	15-Jun-97	17:05	0.11	1.77	1200	1625	117	116	-0.4%	0.4%
9	15-Jun-97	18:00	0.20	1.82	1700	1625	169	176	4.4%	4.4%
10	7-Nov-98	9:11	0.50	1.62	1700	1625	169	179	6.4%	6.4%
11	7-Nov-98	10:25	0.62	2.02	1300	1625	131	131	0.3%	0.3%
12	7-Nov-98	11:33	0.96	2.33	1050	1625	99	100	1.1%	1.1%
13	23-Jun-99	8:51	0.57	1.44	1500	1625	148	158	7.2%	7.2%
14	23-Jun-99	9:54	0.49	1.10	1000	1625	93	103	11.4%	11.4%
15	23-Jun-99	10:59	0.41	0.91	1500	1625	140	160	14.9%	14.9%
16	26-Aug-99	14:02	0.32	1.00	1000	1625	121	103	-15.0%	15.0%
	Average relative error								-0.8%	6.8%
	Minimum relative error								-16.3%	0.3%
	Maximum relative error								14.9%	16.3%
	Standard deviation								9.0%	5.7%

Figure 4 shows head-discharge relationships for S13 resulting from field measurements, the existing and the new rating equations. The continuous curve at the right end represents the pump performance curve close to design engine speed (1200 rpm for the old engines and 1625 rpm for the new ones); the squares (red in color) represent field measurements; the triangles (green in color) represent flows computed using the existing rating equation, and the circles (dark in color) represent flows computed using the new calibrated rating equation. Field discharge values indicate that the actual field performance of the pump is lower than what the manufacturer's curves suggest. This is an expected scenario if the manufacturer's curves are based on model test results under laboratory settings. The decrease could be due to a decrease in pump efficiency, pipe friction losses, aging of the pumps, or other site conditions not accounted for in laboratory settings.

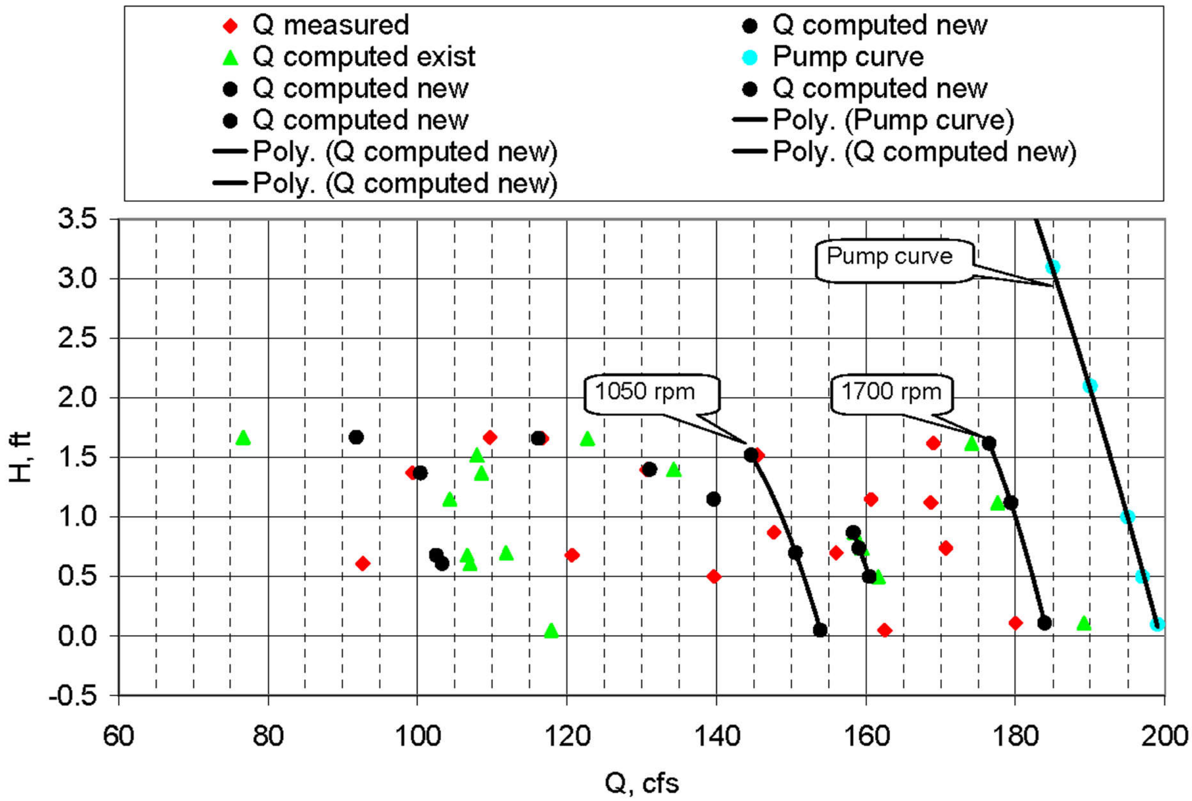

Figure 4. Head and discharge relationship for S13 resulting from field measurements, the existing and the new rating equations

The relative errors of computed discharges using new and existing equations are calculated and shown in Table 12 for all the measurements. As shown in Table 12, the average relative error for the new rating equation is -0.8%, with the relative errors ranging from -16.3% to14.9 %. For the existing rating equation, the average relative error is -6.0%, with the relative errors ranging from -35.1% to 15.7%. The average of absolute relative errors is 6.8% for the new rating equation and it is 14.6% for the existing rating equation.

The percentage of data within selected error ranges from the measured discharge are calculated and shown in Table 13. As shown in Table 13, the new rating has 44% of calculated flows within 5% of the measured discharges, 69% within 10%, and 94% within 15%, while the existing rating equation has 13 % of calculated flows within 5% of the measured discharges, 50% within 10%, and 56% within 15%.

Table 12. Relative errors of computed discharges using new and existing flow equations

No.	Date	Time	Q measured	New rating equation			Existing rating equation		
				Q computed	Relative error	Abs. error	Q computed	Relative error	Abs. error
1	5-Apr-91	14:34	156	151	-3.5%	3.5%	112	-28.3%	28.3%
2	2-Oct-91	14:25	110	92	-16.3%	16.3%	77	-30.1%	30.1%
3	17-Oct-91	13:18	163	154	-5.3%	5.3%	118	-27.5%	27.5%
4	24-Oct-91	13:42	146	145	-0.6%	0.6%	108	-25.8%	25.8%
5	7-Oct-93	12:30	161	140	-13.1%	13.1%	104	-35.1%	35.1%
6	10-Sep-96	13:04	180	184	2.2%	2.2%	189	5.1%	5.1%
7	7-Oct-96	11:27	171	159	-6.8%	6.8%	159	-6.6%	6.6%
8	15-Jun-97	17:05	117	116	-0.4%	0.4%	123	5.2%	5.2%
9	15-Jun-97	18:00	169	176	4.4%	4.4%	174	3.0%	3.0%
10	7-Nov-98	9:11	169	179	6.4%	6.4%	178	5.3%	5.3%
11	7-Nov-98	10:25	131	131	0.3%	0.3%	134	2.8%	2.8%
12	7-Nov-98	11:33	99	100	1.1%	1.1%	109	9.3%	9.3%
13	23-Jun-99	8:51	148	158	7.2%	7.2%	158	7.3%	7.3%
14	23-Jun-99	9:54	93	103	11.4%	11.4%	107	15.5%	15.5%
15	23-Jun-99	10:59	140	160	14.9%	14.9%	162	15.7%	15.7%
16	26-Aug-99	14:02	121	103	-15.0%	15.0%	107	-11.6%	11.6%
	Average relative error				-0.8%	6.8%		-6.0%	14.6%
	Minimum relative error				-16.3%	0.3%		-35.1%	2.8%
	Maximum relative error				14.9%	16.3%		15.7%	35.1%
	Standard deviation				9.0%	5.7%		17.7%	11.1%

Table 13. Percentages of data within selected error ranges from the measured discharges

Criterion on Absolute Relative Error	New Rating Equation	Existing Rating Equation
Percentage of data within 5% of measured discharge	44%*	13%
Percentage of data within 10% of measured discharge	69%	50%
Percentage of data within 15% of measured discharge	94%	56%

*Percentage of measurements out of 16 satisfying the criterion indicated in the first column

9. Impact Analysis

The existing flow rating equation is in case 7 while the new one is in case 8. Since the case number is a non-editable parameter in Flow Trace (a software application developed in-house), we could not use it for impact analysis at the time of this study. An assessment of impact of the new flow rating equation on historical data was performed using breakpoint flows with daily means obtained using IVG (a software application developed in-house) for the period from January 1996 through January 2004.

The existing monthly flow data were obtained from DBHYDRO for the period from January 1996 through January 2004 (period of interest). The monthly flow data for the new rating equation were computed by running IVG program for the same period based on the breakpoint flow data. The breakpoint flow for the new rating equation was calculated using a new Fortran program (code shown in Appendix C). The monthly flow data from the new equation were compared against those from DBHYDRO to assess the impact of the new rating equation on historical data.

Monthly flows are shown in Table 14 for the existing and new flow rating equations for the period of interest. Table 14 shows only the period with flow values. The existing flow column indicates the historical data obtained using the existing rating. The new flow column gives the discharge with the new flow rating equation for pumps at S13. The monthly percent change in flow between the existing and new flow rating equations is indicated in the last column in Table 14. The average of the monthly percent changes between the existing and the new flow rating equations is -7.89%.

10. Conclusion

The existing rating equation yields an average relative error of -6.0% with the relative errors ranging from -35.1% to 15.7%. It has 13% of calculated flows within 5% of measured discharges, 50% within 10%, and 56% within 15%. The existing rating equation can be classified as poor based on the existing criteria. However, with the new rating equation, the average relative error is -0.8% with the relative errors ranging from -16.3% to 14.9%. The new flow rating equation gives 44% of calculated flows within 5% of the measured discharges, 69% within 10%, and 94% within 15%, which improves the rating to fair.

The new rating equation is an improvement over the existing one for pumps at S13. As shown in Table 12, the averages of absolute relative errors are 6.8% and 14.6% for the new and existing rating equations respectively. For all the measurements at S13, the improvement of the average absolute relative error is 7.8%.

An assessment of impact of the new flow rating equation on historical data shows that the average percent change between the existing and the new flow rating equations is -7.89%. At the time of this rating analysis, the historical data produced using the existing flow rating equation are acceptable and can continue to be used for the period before the effective date of the new flow rating equation.

Table 14. Comparison of the existing and the new flow rating equations

DBKEY	Station	Year	Month	Existing flow	New flow	Percent change
16053	S13_P	1996	Jan	0.072	0.068	-5.56%
16053	S13_P	1996	Jun	90.706	83.312	-8.15%
16053	S13_P	1996	Jul	3.823	3.569	-6.64%
16053	S13_P	1996	Sep	51.524	46.136	-10.46%
16053	S13_P	1996	Oct	208.792	188.143	-9.89%
16053	S13_P	1996	Nov	25.899	23.368	-9.77%
16053	S13_P	1996	Dec	27.428	25.467	-7.15%
16053	S13_P	1997	Jan	85.952	78.694	-8.44%
16053	S13_P	1997	Feb	23.842	22.091	-7.34%
16053	S13_P	1997	Jun	229.878	204.812	-10.90%
16053	S13_P	1997	Sep	46.716	42.069	-9.95%
16053	S13_P	1998	Feb	41.169	36.252	-11.94%
16053	S13_P	1998	Apr	1.866	1.731	-7.23%
16053	S13_P	1998	May	16.229	15.408	-5.06%
16053	S13_P	1998	Jun	12.538	11.823	-5.70%
16053	S13_P	1998	Aug	17.344	15.702	-9.47%
16053	S13_P	1998	Sep	201.446	183.008	-9.15%
16053	S13_P	1998	Nov	78.111	71.283	-8.74%
16053	S13_P	1999	Apr	0.055	0.049	-10.91%
16053	S13_P	1999	Jun	204.742	188.101	-8.13%
16053	S13_P	1999	Jul	25.945	23.200	-10.58%
16053	S13_P	1999	Aug	43.143	37.922	-12.10%
16053	S13_P	1999	Sep	75.272	66.560	-11.57%
16053	S13_P	1999	Oct	221.849	202.789	-8.59%
16053	S13_P	1999	Nov	26.570	23.960	-9.82%
16053	S13_P	2000	Jan	0.443	0.381	-14.00%
16053	S13_P	2000	Sep	9.858	8.697	-11.78%
16053	S13_P	2000	Oct	165.570	150.792	-8.93%
16053	S13_P	2000	Nov	9.830	9.110	-7.32%
16053	S13_P	2001	Aug	87.337	84.330	-3.44%
16053	S13_P	2001	Sep	93.692	91.788	-2.03%
16053	S13_P	2001	Oct	89.751	85.437	-4.81%
16053	S13_P	2001	Nov	40.034	37.137	-7.24%
16053	S13_P	2001	Dec	25.080	23.612	-5.85%
16053	S13_P	2002	Jun	55.136	53.682	-2.64%
16053	S13_P	2003	Apr	5.357	5.026	-6.18%
16053	S13_P	2003	May	46.734	44.720	-4.31%
16053	S13_P	2003	Aug	10.348	9.974	-3.61%
16053	S13_P	2003	Nov	13.156	12.865	-2.21%
		Average percent change				-7.89%
		Minimum percent change				-14.00%
		Maximum percent change				-2.03%
		Standard deviation				2.98%

11. Recommendation

The improvement in flow data accuracy is 7.8% for the new flow rating equation. A significant flow data accuracy improvement can be gained by implementing the new rating equation in the Flow program.

It is recommended that the existing rating equation be replaced by the new one. It is further recommended that two to three additional stream flow measurements be used from time to time to verify the performance of the new rating equation. If the new rating equation can not be verified, then seven to twelve additional stream flow measurements should be made to recalibrate the flow equation.

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South Florida Water Management District, West Palm Beach, Florida.

APPENDIX

APPENDIX A

SQL scripts for pump station S13

```
set pagesize 2500
set linesize 200
column Time format a6 word_wrapped
select  distinct x.station, x.meas_date,  to_char (x.meas_date, 'HH24:MI') Time, x.hw_avg HW,
x.tw_avg TW, z.npump Units, x.Discharge Q, x.Discharge_type DisT, y.oper_nr Pump#,
r.case_no case, r.pumpdia pumpdia, y.reading N, r.rpm_noflow Nnoflow,  r.pump_type type,
r.unit_no unit
from qm_main x, qm_operations y, dm_pump z, dm_pump_unit r
where x.station=z.station
and x.station=r.station
and y.oper_nr=r.unit_no
and y.reading>0
and x.Discharge_type='PUMP'
and x.q_meas_id = y.q_meas_id
and x.station = 'S13_P'
order by meas_date, Time
/
```

APPENDIX B

Available measurements for pumps at pump station S13

STATION	MEAS_DATE	TIME	HW	TW	UNITS	Q	CASE	PUMPDIA	N	NNOFLOW	T	UNIT
S13_P	23-Jun-99	8:51	0.57	1.44	3	443	7	5	1500	700	C	1
S13_P	23-Jun-99	8:51	0.57	1.44	3	443	7	5	1500	700	C	2
S13_P	23-Jun-99	8:51	0.57	1.44	3	443	7	5	1500	700	C	3
S13_P	7-Nov-98	9:11	0.5	1.62	3	506	7	5	1700	700	C	1
S13_P	7-Nov-98	9:11	0.5	1.62	3	506	7	5	1700	700	C	2
S13_P	7-Nov-98	9:11	0.5	1.62	3	506	7	5	1700	700	C	3
S13_P	23-Jun-99	9:54	0.49	1.1	3	278	7	5	1000	700	C	1
S13_P	23-Jun-99	9:54	0.49	1.1	3	278	7	5	1000	700	C	2
S13_P	23-Jun-99	9:54	0.49	1.1	3	278	7	5	1000	700	C	3
S13_P	7-Nov-98	10:25	0.62	2.02	3	392	7	5	1300	700	C	1
S13_P	7-Nov-98	10:25	0.62	2.02	3	392	7	5	1300	700	C	2
S13_P	7-Nov-98	10:25	0.62	2.02	3	392	7	5	1300	700	C	3
S13_P	23-Jun-99	10:59	0.41	0.91	3	419	7	5	1500	700	C	1
S13_P	23-Jun-99	10:59	0.41	0.91	3	419	7	5	1500	700	C	2
S13_P	23-Jun-99	10:59	0.41	0.91	3	419	7	5	1500	700	C	3
S13_P	7-Oct-96	11:27	0.86	1.6	3	512	7	5	1500	700	C	1
S13_P	7-Oct-96	11:27	0.86	1.6	3	512	7	5	1500	700	C	2
S13_P	7-Oct-96	11:27	0.86	1.6	3	512	7	5	1500	700	C	3
S13_P	7-Nov-98	11:33	0.96	2.33	3	298	7	5	1050	700	C	1
S13_P	7-Nov-98	11:33	0.96	2.33	3	298	7	5	1050	700	C	2
S13_P	7-Nov-98	11:33	0.96	2.33	3	298	7	5	1050	700	C	3
S13_P	10-Jun-96	11:37	1.64	0.86	3	537	7	5	1600	700	C	1
S13_P	10-Jun-96	11:37	1.64	0.86	3	537	7	5	1600	700	C	2
S13_P	10-Jun-96	11:37	1.64	0.86	3	537	7	5	1600	700	C	3
S13_P	7-Oct-93	12:30	1.1	2.25	3	482	7	5	1000	700	C	1
S13_P	7-Oct-93	12:30	1.1	2.25	3	482	7	5	1000	700	C	2
S13_P	7-Oct-93	12:30	1.1	2.25	3	482	7	5	1000	700	C	3
S13_P	10-Sep-96	13:04	11.24	11.35	3	540	7	5	1700	700	C	1
S13_P	10-Sep-96	13:04	11.24	11.35	3	540	7	5	1700	700	C	2
S13_P	10-Sep-96	13:04	11.24	11.35	3	540	7	5	1700	700	C	3

STATION	MEAS_DATE	TIME	HW	TW	UNITS	Q	CASE	PUMPDIA	N	NNOFLOW	T	UNIT
S13_P	17-Oct-91	13:18	1.13	1.18	3	325	7	5	1050	700	C	1
S13_P	17-Oct-91	13:18	1.13	1.18	3	325	7	5	1050	700	C	2
S13_P	24-Oct-91	13:42	0.52	2.04	3	291	7	5	1050	700	C	1
S13_P	24-Oct-91	13:42	0.52	2.04	3	291	7	5	1050	700	C	2
S13_P	10-Sep-96	13:49	11.24	11.17	3	366	7	5	1700	700	C	1
S13_P	10-Sep-96	13:49	11.24	11.17	3	366	7	5	1700	700	C	2
S13_P	26-Aug-99	14:02	0.32	1	3	362	7	5	1000	700	C	1
S13_P	26-Aug-99	14:02	0.32	1	3	362	7	5	1000	700	C	2
S13_P	26-Aug-99	14:02	0.32	1	3	362	7	5	1000	700	C	3
S13_P	2-Oct-91	14:25	0.06	1.73	3	329	7	5	750	700	C	1
S13_P	2-Oct-91	14:25	0.06	1.73	3	329	7	5	750	700	C	2
S13_P	2-Oct-91	14:25	0.06	1.73	3	329	7	5	750	700	C	3
S13_P	5-Apr-91	14:34	0.54	1.24	3	468	7	5	1050	700	C	1
S13_P	5-Apr-91	14:34	0.54	1.24	3	468	7	5	1050	700	C	2
S13_P	5-Apr-91	14:34	0.54	1.24	3	468	7	5	1050	700	C	3
S13_P	15-Jun-97	17:05	0.11	1.77	3	350	7	5	1200	700	C	1
S13_P	15-Jun-97	17:05	0.11	1.77	3	350	7	5	1200	700	C	2
S13_P	15-Jun-97	17:05	0.11	1.77	3	350	7	5	1200	700	C	3
S13_P	15-Jun-97	18:00	0.2	1.82	3	507	7	5	1700	700	C	1
S13_P	15-Jun-97	18:00	0.2	1.82	3	507	7	5	1700	700	C	2
S13_P	15-Jun-97	18:00	0.2	1.82	3	507	7	5	1700	700	C	3

APPENDIX C

Fortran codes for breakpoint flow

```
C     This program is designed to compute breakpoint flow using new rating equation (case 8)
C     for pump station S13. The output file will be used for running IVG program. The result of
C     mean monthly flow will be used for impact analysis on historical data.

C     file meaning
C     DCVP bkpt input data obtained by running bkptflow
C     bkptinput.dat     breakpoint input data for headwater, tailwater, and engine speed
C     bkpt1.dat    breakpoint flow obtained using existing rating equation
C     bkpt2.dat    breakpoint flow output file generated from new rating equation

C     symbol meaning
C     Id          Site ID
C     T           time(24 hours)
C     Tag         tag data type
C     N0          design engine speed
C     N1          engine speed for pump 1
C     N2          engine speed for pump 2
C     N3          engine speed for pump 3
C     Q_P1        flow in pump unit 1
C     Q_P2        flow in pump unit 2
C     Q_P3        flow in pump unit 3
C     Q           total flow using new rating equation (Q=Q_P1+Q_P2+Q_P3)
C     H_W         headwater elevation
C     T_W         tailwater elevation
C     H           head differential

C     new rating equation in case 8
C     A,B,C, and D are coefficients and exponent

C     start program
      program bkptflow
      implicit none
      intrinsic Abs
      integer, parameter :: N0=1625, LIMIT=25000
      integer :: Loop
      real ,parameter :: A=176.0,B=-4.4, C=1.3,D=1.6
      real :: Q,Q_P1,Q_P2,Q_P3,H_W,T_W,H,N1,N2,N3
      integer, parameter :: S_ID=16, TIME=4, DATA_T=1
      character (len=S_ID) :: Id
      character (len=TIME) :: T
      character (len=DATA_T) :: Tag
```

```
        open(unit=5,  file='bkptinput.dat',status ='unknown')
        open(unit=10, file='bkpt1.dat', status='unknown')
        open(unit=30, file='bkpt2.dat', status='unknown')

        do Loop=1,LIMIT
C             compute bkptflow using new rating equation
C             read input data from existing bkptinput file
              read(5,50)H_W, T_W, N1, N2, N3
 50           format(28x,F5.3,5x,F5.3,4x,F8.3,2x,F8.3,2x,F8.3)
             H=Abs(H_W-H_W)
C             compute Q_P1
C             no flow at engine speed below 700 rpm
                    if (N1>700) then
                         Q_P1= A*(N1/N0)+B*H**C*(N0/N1)**D
                          else
                         Q_P1=0
                          end if
C              compute Q_P2
C              no flow at engine speed below 700 rpm
                    if (N2>700) then
                       Q_P2= A*(N2/N0)+B*H**C*(N0/N2)**D
                        else
                        Q_P2=0
                         end if
C               compute Q_P3
C               no flow at engine speed below 700 rpm
                      if (N3>700) then
                            Q_P3= A*(N3/N0)+B*H**C*(N0/N3)**D
                             else
                             Q_P3=0
                             end if
C              compute Q
               Q=Q_P1+Q_P2+Q_P3
C                read site I.D. , Time, and data type from existing bkptflow file
                read (10, 100) Id, T,Tag
 100            format (A16,1x,A4,9x,A1)
C               write output file for bkptflow for new rating equation
                write(30,200) Id,T,Q,Tag
 200            format(A16,1x,A4,2x,F7.3,A1)
          end do
          close (5)
          close (10)
          close (30)
          end program bkptflow
```