FLOW RATING ANALYSIS FOR PUMP STATION G600

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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DEFINITIONS

Acronyms

ADCP	Acoustic Doppler Current Profiler
CI	Confidence interval
NLIN	Nonlinear regression procedure in SAS software
TDH	Total dynamic head
TSH	Total static head
SFWMD	South Florida Water Management District

EXECUTIVE SUMMARY

We conducted a rating analysis for Pump Station G600 based on the conventional Case 8 model. We developed a new rating equation based on the measured flow data since there is no factory pump performance curve available for G600. The new rating is in good agreement with the measured flows, and we recommend that the new rating equation be implemented to compute flows through Pump Station G600 in DBHYDRO.

We performed an impact analysis to evaluate the need to recompute the historical flows through Pump Station G600 for the period of record from October 29, 1997 through December 2, 2010. A comparison between the daily flows computed using the existing and new rating equation indicates that the average absolute relative difference between the two sets of flows is about 13%. It appears that the existing rating equation overestimates flows though PUMP Station G600. We recommend that the historical flows be recomputed with the new rating equation, and be reloaded into DBHYDRO.

1.0 INTRODUCTION

1.1 Background

The Pump Station G600 is located at the northwestern corner of STA-6, Section 1, directly east of the L-3 Borrow Canal in Hendry County, as shown in **Figure 1**.

The station serves as a primary inflow control structure for STA-6, Section 1. United States Sugar Corporation owns and operates this station. Surface Water Management Permit No.26-00041-S (issued by the District) authorizes the operation of this facility. The pump station used to consist of five diesel pumps, each has a design capacity of 100 cfs. There are currently four pump units left in operation since pump unit one burned out in September 2004. Three of the pumps also have the ability for reverse operation.

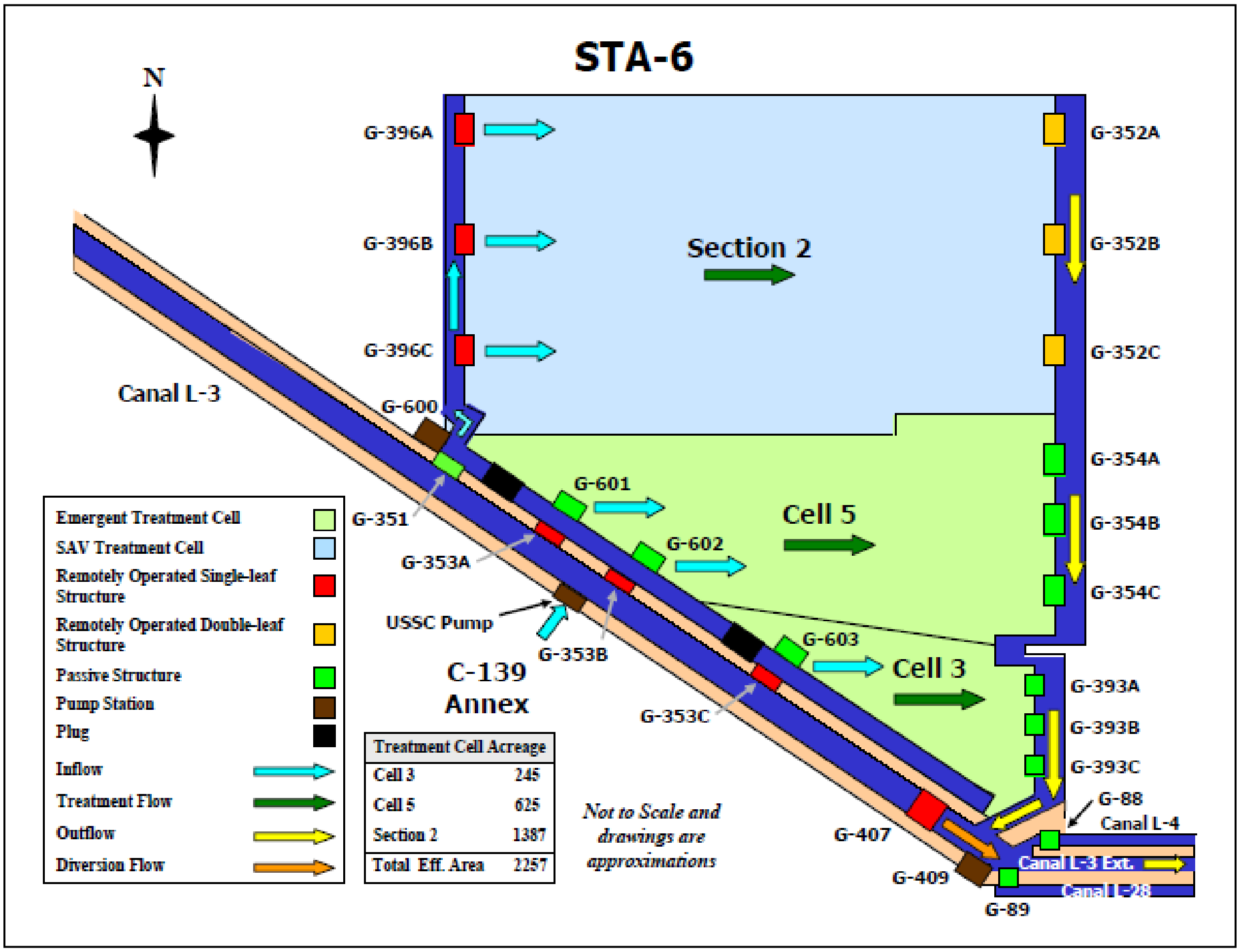

Figure 1. Location Map for Pump Station G600

1.2 Objectives and Scope

The purpose of the rating analysis is to improve the existing rating equation for Pump Station G600 since the water budget analyses conducted by the District staff in 2006 indicate that the existing rating overestimates the flows through G600. We develop the new rating equation based on measured flow data since the factory pump performance curve is not available for this pump station. We compare the new rating equation to the existing rating equation along with the measured flows. We also conduct impact analysis to evaluate the need to recalculate the historical flow records in DBHYDROL.

2.0 STATION DESIGN

A plan view of the pump station design is shown in **Figure 2**. **Figure 3** illustrates the elevation of the pump station, and **Figure 4** shows vertical profile of the pump.

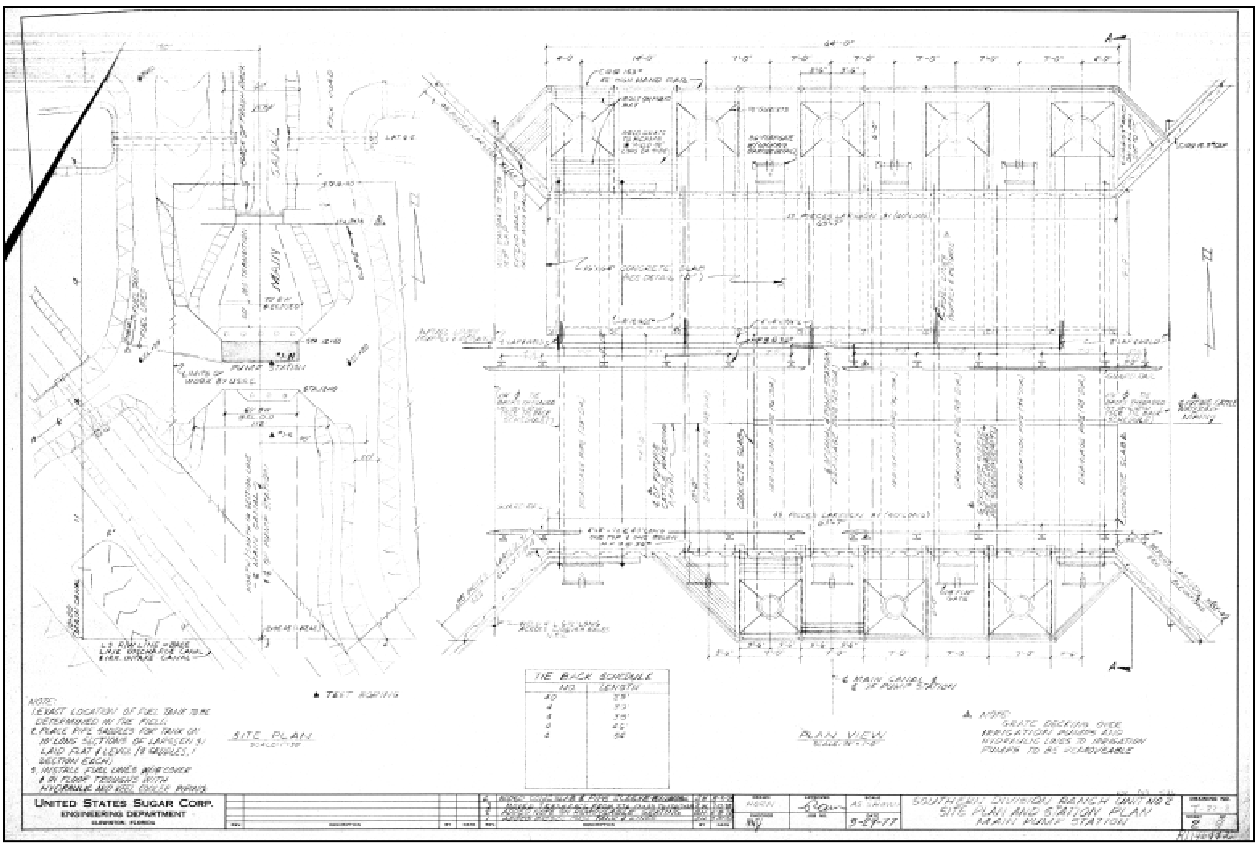

Figure 2. Plan View of the Pump Station Design

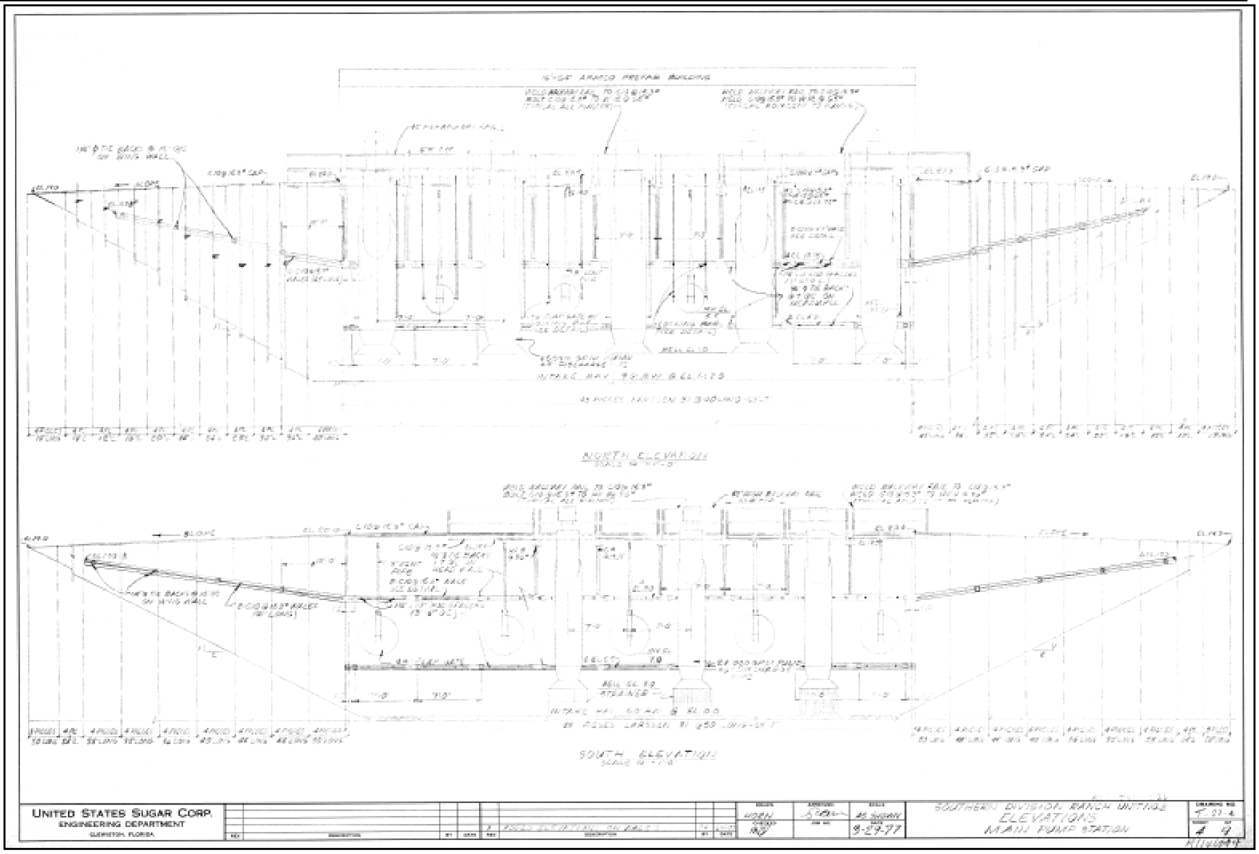

Figure 3. Pump Station Elevation

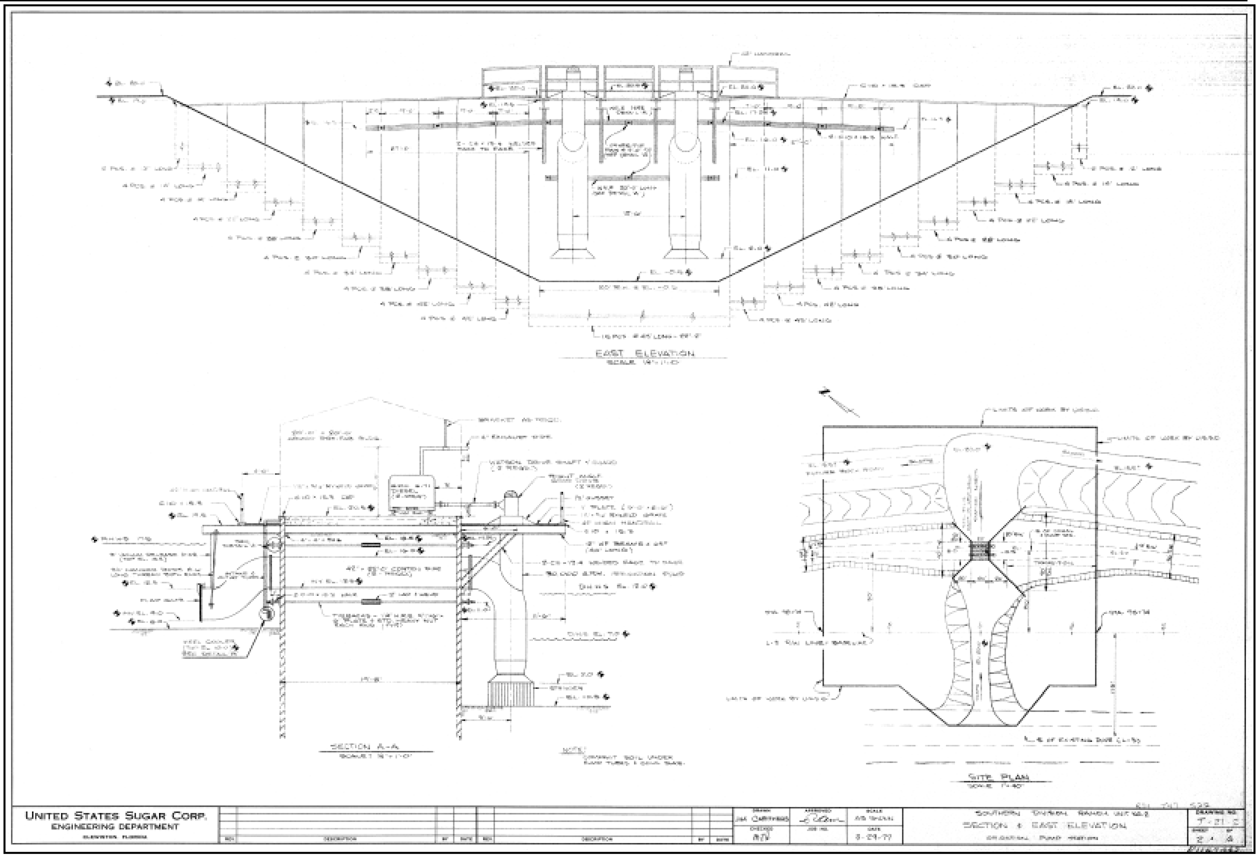

Figure 4. Pump Vertical Profile

3.0 STREAM FLOW DATA

There are thirteen measured flow data for this station in the streamgauging database. The flow measurement was conducted using an Acoustic Doppler Current Profiler (ADCP) between 2001 and 2006. **Table 1** summarizes these flow measurements, including the static head, number of pumps in operation, average discharge, average engine speed, and measurement quality tag.

The static head is calculated as the difference between the effective tailwater elevation and the monitored headwater elevation at pump Station G600 (G600-H). The effective tailwater elevation is the maximum of the discharge pipe centerline elevation, and the monitored tailwater elevation (G600-T).

The quality of each flow measurement has been evaluated and assigned quality tag or qualitative accuracy qualifier. There are five categories of qualifiers are used: “excellent”, “good”, “fair”, “poor”, and “bad”. **Table 1** indicates that among these thirteen measured flows, there is one with “Bad”, six with “Poor”, five with “Fair”, and one with “Good” quality tag. Based on the District’s Standard Operation Procedure (SOP) (SFWMD, 2009), the flow data with “Poor” or “Bad” measurement quality tag should not be used for rating analysis. However, our initial investigation indicated that four measured flows with “Poor” quality tag show a reasonable agreement with the flows calculated from the rating equation updated previously, having absolute relative errors less than 10%. Hence, we decided to include these four measured flow data in our new rating analysis. The ten measured flow data highlighted in **Table 1** (in Bold) are used for the new rating analysis.

Table 1. Summary of Flow Measurements

Measure-ment Date	Average HW El (ft, NGVD)	Average TW El. (ft, NGVD)	Total Static Head (ft)	# Units in Operation	Average Engine Speed (rpm)	Average Discharge (cfs)	95% C.I. Error		Quality Tag
							Bootstrap Error	t-dist Error	
10/25/01	7.78	15.55	7.77	4	1537.50	57.498	10.9	19.5	Bad
07/29/04	**9.83**	**15.24**	**5.41**	**2**	**1599.50**	**69.300**	**2.4**	**3.7**	**Poor**
08/03/04	**11.12**	**15.52**	**4.40**	**3**	**1638.00**	**77.284**	**1.9**	**3.6**	**Good**
08/17/04	**10.02**	**15.41**	**5.39**	**3**	**1733.33**	**81.674**	**5.3**	**9.7**	**Fair**
08/18/04	**8.58**	**15.21**	**6.63**	**1**	**1695.72**	**81.420**	**1.8**	**3.3**	**Fair**
03/13/05	**8.15**	**15.32**	**7.17**	**1**	**1700.00**	**66.902**	**0.6**	**1.1**	**Poor**
03/19/05	**7.79**	**15.62**	**7.83**	**2**	**1700.00**	**65.629**	**5.8**	**10.5**	**Poor**
03/21/05	**8.30**	**15.66**	**7.36**	**2**	**1700.00**	**76.308**	**4.6**	**8.4**	**Poor**
01/04/06	**9.88**	**13.42**	**3.54**	**1**	**1928.00**	**82.635**	**3.8**	**7**	**Fair**
01/04/06	10.05	13.60	3.55	1	1495.00	45.665	3.2	4.2	Poor
08/25/06	**9.05**	**14.91**	**5.86**	**1**	**1511.00**	**70.404**	**2.4**	**4.4**	**Fair**
10/27/06	**9.00**	**14.97**	**5.97**	**1**	**1624.00**	**72.839**	**3.2**	**5.7**	**Fair**
11/17/06	7.70	14.93	7.23	1	1599.00	50.77	0.7	1.3	Poor

4.0 RATING ANALYSIS

4.1 Existing Rating Equation

The existing pump rating equation is based on the Case 6 model, as shown below:

$$Q = 0.00223 \cdot C_2 \cdot \frac{N}{C_0} \cdot \left\{ C_1 - \left[\frac{\left(\frac{C_0}{N}\right)^2 \cdot H - C_3}{\left|\left(\frac{C_0}{N}\right)^2 \cdot H - C_3\right|} \right] \left[\left| \left(\frac{C_0}{N}\right)^2 \cdot H - C_3 \right| \right]^{1/3} \right\} \tag{1}$$

Where

Q: Discharge in cfs;
H: Total static head (TSH) – head difference between upstream and downstream stages in ft;
N: Pump engine speed in rpm;
C_0-C_3: Regression coefficients.

Table 2 lists the coefficients of the pump units at Pump Station G600.

Table 2. Regression Coefficients for G600

Pump Unit	C_0	C_1	C_2	C_3
#1	1800	-1.1	36000	19
#2	1800	-1.1	29250	21
#3	1800	-1.1	29000	19
#4	1800	-1.1	32000	20
#5	1800	-1.1	36000	19

Based on the water budget analysis conducted by Huebner Richard in 2006, it appears that the discharge computed by Eq. (1) overestimates flows through Pump Station G600.

The study of Akpoji et al, (2003) defines that the rating can be classified as “excellent” when 95% of the computed flows are within 5% of the measured flows, “good” if they are within 10%, “fair” if they are within 15% and “poor” when they are not within 15%.

The quality of the existing rating equation was evaluated by comparing the calculated discharges to the measured ones. **Table 3** presents the comparison between the computed and measured discharges. The average absolute relative error is 15.6% and the percentage of data with absolute relative errors within 15% is only 40%, much less than 95%.

Table 3. Comparison between Measured and Computed Discharges for the Existing Rating Equation (Case 6)

No.	Measurement Date	Head Water Elevation (ft, NAVD)	Tail Water Elevation (ft, NAVD)	Q measured (cfs)	Q computed (cfs)	Relative Error (%)	Absolute Relative Error (%)
1	07/29/04	9.83	15.24	138.60	165.43	19.4	19.4
2	08/03/04	11.12	15.52	231.85	271.02	16.9	16.9
3	08/17/04	10.02	15.41	245.02	275.60	12.5	12.5
4	08/18/04	8.58	15.21	81.42	78.83	-3.2	3.2
5	03/13/05	8.15	15.32	66.90	85.02	27.1	27.1
6	03/19/05	7.79	15.62	131.26	157.90	20.3	20.3
7	03/21/05	8.30	15.66	152.62	163.00	6.8	6.8
8	01/04/06	9.88	13.42	82.64	98.04	18.6	18.6
9	08/25/06	9.05	14.91	70.40	59.85	-15.0	15.0
10	10/27/06	9.00	14.97	72.84	84.60	16.1	16.1
Average						12.0	15.6
Minimum						-15.0	3.2
Maximum						27.1	27.1
% of data with Absolute Relative Error <=5% (Rating is very good)							10
% of data with 5% < Absolute Relative Error <=10% (Rating is good)							10
% of data with 10% < Absolute Relative Error <=15% (Rating is fair)							20
% of data with Absolute Relative Error >15% (Rating is poor)							60

4.2 New Rating Equation

We use Case 8 rating model for the new rating analysis. Case 8 rating equation is developed by dimensional analysis and the pump affinity laws, which is the conventional rating equation representing all the possible cases, as documented in Damisse (2001), Imru and Wang (2003). Equation (2) below shows the Case 8 rating equation.

$$Q = A\left(\frac{N}{No}\right) + BH^{C}\left(\frac{No}{N}\right)^{2C-1} \qquad (2)$$

Where

Q: Discharge in cfs;
N: Pump engine speed in rpm;
No: Design pump engine speed in rpm (1800 rpm);
H: Total static head (TSH);
A, *B* and *C*: Regression parameters determined through regression analysis.

The *H* versus *Q* relationship is usually determined by subtracting the head losses through the intake and discharge works from each point on the pump performance curve. This results in a station performance curve for each pump. The station performance curve can then be calibrated using available measured flow data. However, there is no pump performance curve available for this pump station. Measured flow data in **Table 1** are used to estimate the coefficients in equation (2).

In the present rating analysis, we only need to estimate rating coefficients for one pump unit since all four pump units of G600 have the same design engine speed (1800 rpm) and the same design discharge (100 cfs). We conducted a nonlinear regression analysis using SAS NLIN function to determine the coefficients in equation (2). **Table 4** presents the resultant regression coefficients along with their approximate 95% confidence limits. There are no confidence limits for coefficient B. In the regression analysis, we set the constraint for the minimum value of coefficient as B ≤ -0.008 because coefficient B could be very close to or equal to zero if we hadn't done so, and equation (2) could become linear equation and were only the function of pump engine speed N and coefficient A, which is not reasonable. This is mainly due to the limited number of measured flow data.

Table 4. Case 8 Rating Coefficients for G600

Regression Coefficient	Estimate	Approximate lower 95% Confidence Limit	Approximate upper 95% Confidence Limit
A	83.3645	75.3097	91.4193
B	-0.0080		
C	3.1254	2.2494	4.0013

We evaluated the quality of the new rating equation by comparing the calculated discharges to the measured ones. **Table 5** presents the comparison between the measured and computed discharges. The average absolute relative error is 6.0%. The percentage of data with absolute relative errors within 5% is 50, with absolute relative errors between 5% and 10% is 40, and with absolute relative errors between 10% and 15% is 10. The percentage of data with absolute relative error <=15% is 100.

Table 5. Comparison between Measured and Computed Flows for New Rating Equation (Case 8)

No.	Measurement Date	Head Water Elevation (ft, NAVD)	Tail Water Elevation (ft, NAVD)	Q measured (cfs)	Q computed (cfs)	Relative Error (%)	Absolute Relative Error (%)
1	07/29/04	9.83	15.24	138.60	142.34	2.7	2.7
2	08/03/04	11.12	15.52	231.85	223.48	-3.6	3.6
3	08/17/04	10.02	15.41	245.02	235.09	-4.1	4.1
4	08/18/04	8.58	15.21	81.42	74.49	-8.5	8.5
5	03/13/05	8.15	15.32	66.90	73.64	10.1	10.1
6	03/19/05	7.79	15.62	131.26	144.04	9.7	9.7
7	03/21/05	8.30	15.66	152.62	146.41	-4.1	4.1
8	01/04/06	9.88	13.42	82.64	89.00	7.7	7.7
9	08/25/06	9.05	14.91	70.40	64.94	-7.8	7.8
10	10/27/06	9.00	14.97	72.84	71.56	-1.8	1.8
Average						0.0	6.0
Minimum						-8.5	1.8
Maximum						10.1	10.1
% of data with Absolute Relative Error <=5% (Rating is excellent)							50
% of data with 5% < Absolute Relative Error <=10% (Rating is good)							40
% of data with 10% < Absolute Relative Error <=15% (Rating is fair)							10
% of data with Absolute Relative Error >15% (Rating is poor)							0

We also compared the measured discharges with the computed ones from both the existing rating (Case 6) and the new rating (Case 8), as shown in **Figure 5**. **Figure 5** visualizes that the discharges computed from the new rating equation show much better agreement with the measured discharges than those from the existing equation.

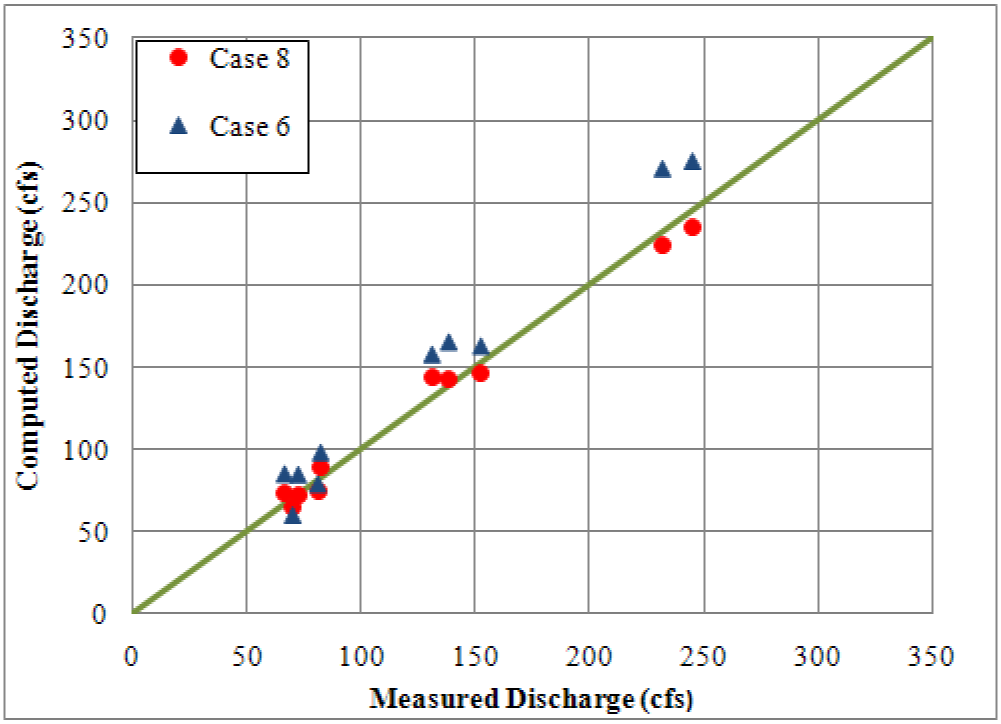

Figure 5. Comparison of Agreement between Measured and Computed Discharges

In order to further evaluate the goodness-of-fit of the new rating to the measured flows, we divide the measured flow data into six plotting groups according to their measured engine speed, as listed in **Table 6**. **Table 6** also presents the upper and lower 95% confidence limit errors based on the t-distribution.

Table 6. Six Plotting Groups of Measured Data

Average HW El (ft, NGVD)	Average TW El. (ft, NGVD)	Total Static Head (ft)	Average Discharge (cfs)	Average Engine Speed (rpm)	95% t-Dist. Error	Plotting Group RPM
9.05	14.91	5.86	70.404	1511	±4.4	**1510**
9.83	15.24	5.41	69.300	1600	±3.7	**1600**
9.00	14.97	5.97	72.839	1624	±5.7	**1630**
11.12	15.52	4.40	77.284	1638	±3.6	
8.58	15.21	6.63	81.420	1696	±3.3	**1700**
8.15	15.32	7.17	66.902	1700	±1.1	
7.79	15.62	7.83	65.629	1700	±10.5	
8.30	15.66	7.36	76.308	1700	±8.4	
10.02	15.41	5.39	81.674	1733	±9.7	**1730**
9.88	13.42	3.54	82.635	1928	±7.0	**1930**

Figure 6 shows the comparison of the new rating curves to the measured flows along their 95% confidence intervals at given engine speed *N* = 1510, 1600, 1630, 1700, 1730, and 1930 rpm, which indicates that these rating curves fall within the confidence intervals of the corresponding measured flows, except for the rating curve at N = 1510 rpm that is outside of the 95% confidence interval of the measured data (70.40, 5.86) , and the rating curve at N = 1700 rpm that is outside of the 95% confidence intervals of the measured data (66.70, 7.17) and (81.42, 6.63). The diagram also indicates that more measurements are needed to further improve the rating.

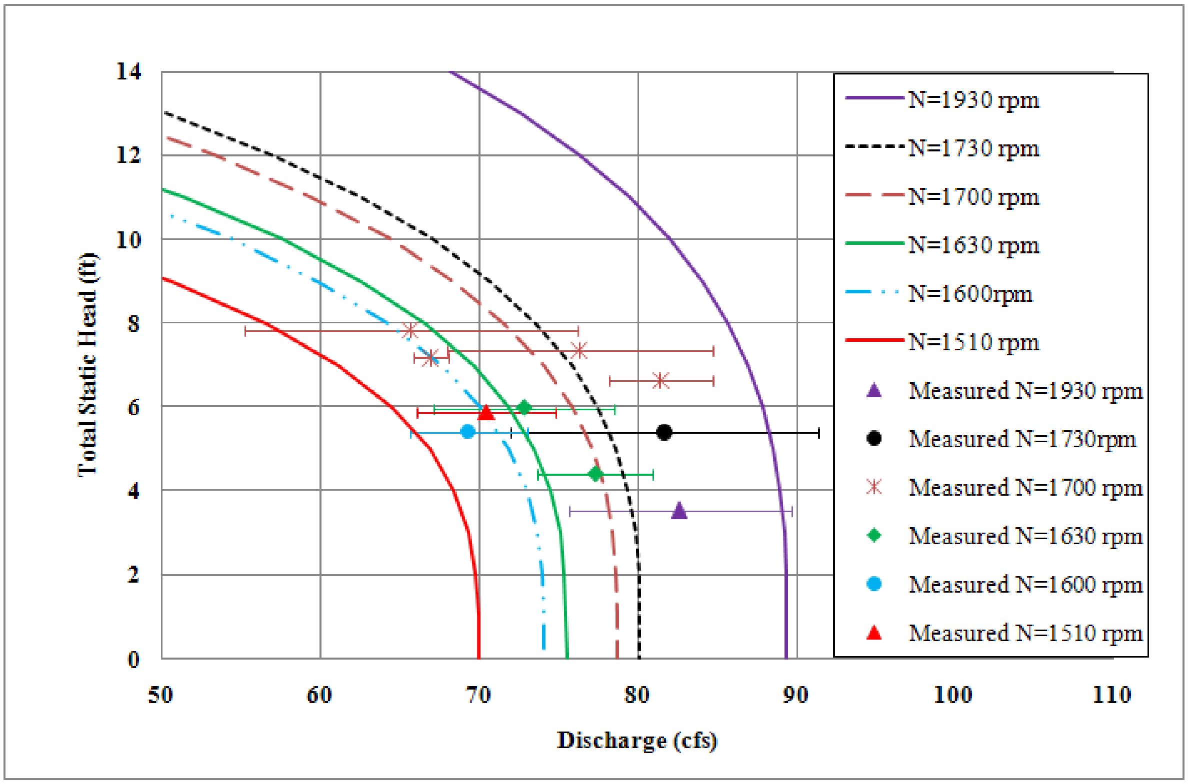

Figure 6. Head and Discharge Relationship for G600

4.3 Upper and Lower 95% Confidence Limits for New Rating Equation

To further investigate the suitability of this new equation for representing the relationship between total static head and discharge at Pump Station G600, we derived the upper and lower 95% confidence limits of the rating curve at engine speed = 1800 rpm. For the purpose of comparison of the measured flow data to the pump rating curve, we first converted using the pump affinity laws the measured TSHs and discharges to the values corresponding to a given engine speed of 1800 rpm, as suggested by Damisse (2011, personal conversation). **Table 7** presents the converted TSHs and flows corresponding to 1800 rpm.

Table 7. Converted TSH and Discharges

Measured Data			Measured Data Converted		
N (rpm)	TSH (ft)	*Q* measured (cfs)	N_0 (rpm)	TSH_0 (ft)	Q_0 (cfs)
1700.0	7.83	65.63	1800	8.78	69.49
1700.0	7.36	76.31	1800	8.25	80.80
1700.0	7.17	66.90	1800	8.04	70.84
1695.7	6.63	81.42	1800	7.47	86.43
1624.0	5.97	72.84	1800	7.33	80.73
1511.0	5.86	70.40	1800	8.32	83.87
1599.5	5.41	69.30	1800	6.85	77.99
1733.3	5.39	81.67	1800	5.81	84.82
1638.0	4.4	77.28	1800	5.31	84.93
1928.0	3.54	82.64	1800	3.09	77.15

The upper/ lower confidence interval (CI) of the regression equation (rating equation) can be generated using the asymptotic method (Motulsky and Christopoulos, 2003) as given below:

(3)

Where

: Upper (+) and Lower (-) confidence limits at a given significance level (α)

s: Standard error of estimate or standard deviation of the residuals. In this study *s* = 5.14.

: A point on Student's t distribution, and its value is the function of degree of freedom (df = *n*-3) and confidence interval 100(1 -)%. In this study, = 2.841 for the confidence interval of 95% and df = 7.

Figure 7 shows the confidence intervals of the pump rating curve alone with the measured TSH and discharges. Figure 7 indicates that all the measured discharges are within the 95% confidence interval.

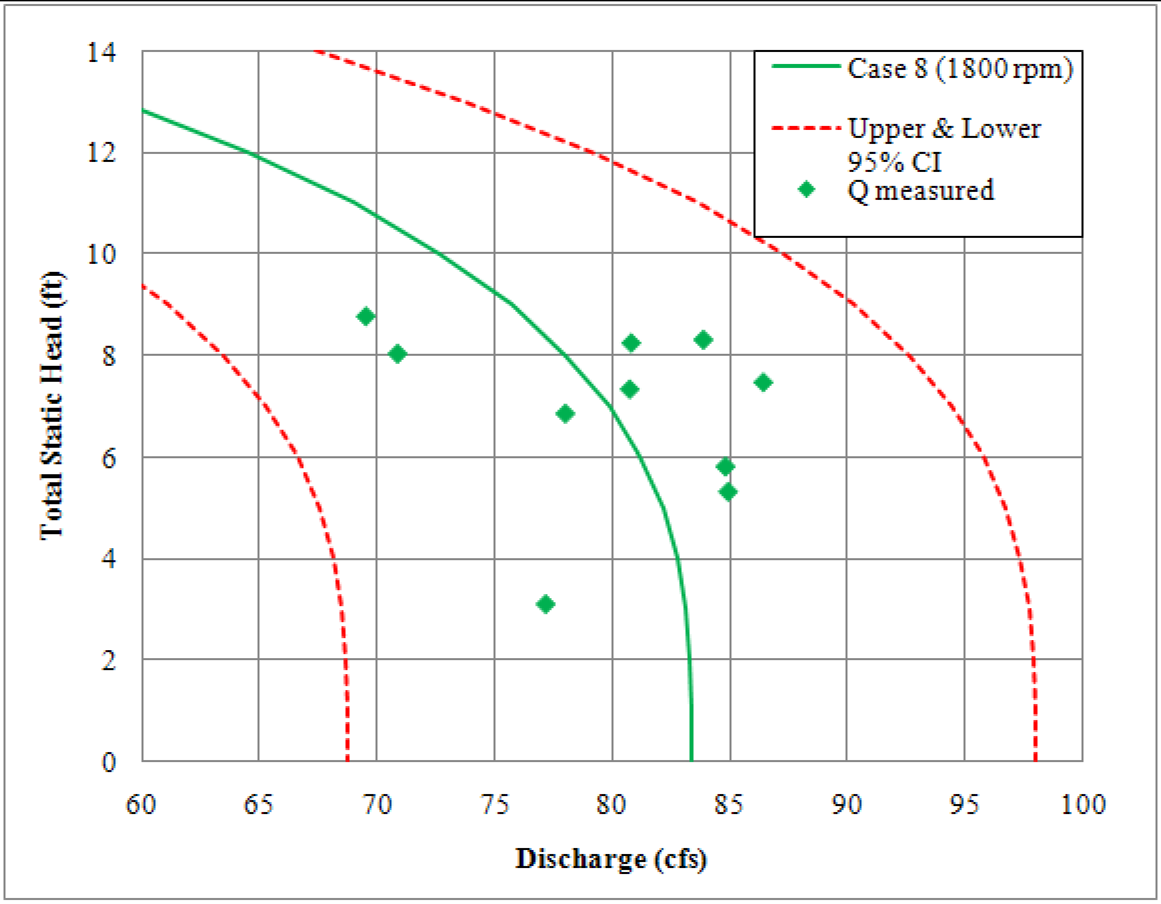

Figure 7. The 95% Confidence Intervals of Pump Rating Curve

5.0 IMPACT ANALYSIS

In order to assess if the historical flow data need to be recomputed using the new rating equation, we conducted an impact analysis over the period of record spanning October 29, 1997 through December 2, 2010.

The impact analysis involved the evaluation of the differences between the flows computed using the existing and new rating equation. **Table 8** presents a summary of the difference in daily flows per year. There are 2448 days when flows occurred during the period of interest. The average absolute relative difference in computed daily flows between the existing and new rating equations is about 13%, with differences ranging from -33% to 32%. There are 1944 days with absolute relative differences equal to or larger than 5 percent, which is about 79% of total number of days when flows occurred. **Figure 8** illustrates the absolute relative difference in average daily flows for the period of record. **Table 9** presents the annual flow volume comparison between the existing and new rating, which indicates that the flow volume from the existing rating equation over the period of record is about 10% more than that from the new rating equation.

Table 8. Summary of Impact Analysis for G600

Year	Number of Days with Flow	Minimum Difference (%)	Maximum Difference (%)	Average Relative Difference (%)	Average Absolute Relative Difference (%)	Absolute Relative Differences > = 5%	
						Number of Days	%
1997	49	-18	2	-7	7	35	71
1998	211	-33	2	-11	11	191	91
1999	235	-31	12	-10	11	199	85
2000	153	-29	11	-14	14	139	91
2001	205	-25	0	-12	12	191	93
2002	255	-30	5	-9	9	197	77
2003	281	-31	11	-7	8	175	62
2004	135	-25	19	-12	13	129	96
2005	89	-30	-2	-17	17	86	97
2006	268	-27	19	-10	12	235	88
2007	4	-27	-27	-27	27	4	100
2008	2	-27	-26	-26	26	2	100
2009	252	-27	21	-2	8	166	66
2010	309	-19	32	-1	8	195	63
Entire Period	**2448**	**-33**	**32**	**-12**	**13**	**1944**	**79**

Table 9. Annual Flow Volume Comparison between Existing and New Rating

Year	Existing Rating (Case 6) (ac-ft)	New Rating (Case 8) (ac-ft)	Relative Difference (%)
1997	12111	11273	-7
1998	52080	46443	-11
1999	60498	54096	-11
2000	37034	31736	-14
2001	48253	42561	-12
2002	54993	50208	-9
2003	59573	55494	-7
2004	25097	21938	-13
2005	32308	26142	-19
2006	40524	36007	-11
2009	38784	37682	-3
2010	35707	35030	-2
Average			**-10**

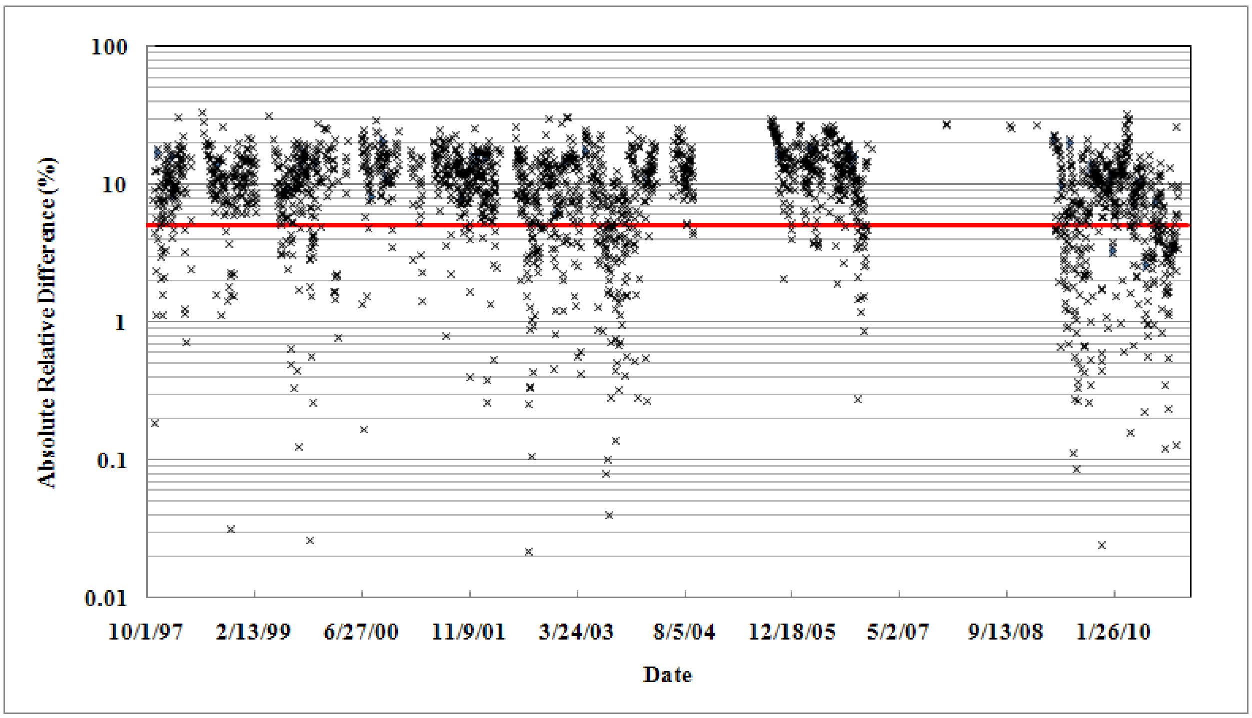

Figure 8. Absolute Relative Difference between Daily Flows Computed by Existing and New Rating Equations.

The Change Management Procedure for Hydrometeorological Data in the District's Hydrologic Database (Damisse et al, 2009) indicates that the historical flows computed using the existing equation are subject to modification if one or more records in any flow time-series deviate at least 5% from the corresponding new flow records. Therefore, we recommend that the historical flows through Pump Station G600 be recomputed with the proposed rating equation and subsequently be reloaded into DBHYDROL.

6.0 STREAMGAUGING NEEDS

We developed the new rating equation based solely on 10 measured flow data. In order to improve the new rating equation, more measured flow data are required for Pump Station G600. **Table 10** summarizes the desired number of flow measurements under each of the pump operating conditions.

Table 10. Stream Gauging Needs for Pump Station G600

Total Static Head (ft)	Number of Measurements required at Specified Pump Engine Speed		
	1600 rpm	1800 rpm	2000 rpm
0-3	3	4	5
3-6			5
6-9	3	4	5

7.0 SUMMARY AND CONCLUSIONS

A rating analysis of Pump Station G600 was carried out using the conventional case 8 model. We developed the new rating equation based on measured flow data. The computed flows by the new rating equation are in good agreement with the measured flows, and all the measured flows are within the 95% confidence interval of the new rating curve at the engine speed of 1800 rpm. We recommend that the new rating equation be implemented to generate flows through Pump Station G600.

We conducted an impact analysis to evaluate if historical flows through pump station G600 need to be recomputed. A comparison between the daily flows computed using the existing and new rating equation indicates that the average absolute relative difference between the two sets of flows is about 13%, and hence we recommend that the historical flows be recomputed with the new rating equation, and be reloaded into DBHYDRO.

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