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RATING ANALYSIS FOR PUMP STATION G310

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EXECUTIVE SUMMARY

This document summarizes the results of rating analysis, model development and calibration for flow through the pumps at G310. G310 is a six unit pump station located at the south corner of Stormwater Treatment Area 1 West (STA-1W) approximately 400 feet east and 1,500 feet north of the southeast corner of Section 34, Township 44 South, Range 39 East in Palm Beach County.

There are twenty two field flow measurements for pump station G310 and all of the measurements are used for this rating analysis. The rating analysis results show that the relative errors in discharge vary from -5.78% to 28.45 % and the average relative error is 3.35% for the existing rating equations. The evaluation and analysis results show that flow data accuracy can be further improved by using the new rating equations developed, calibrated, and presented here.

The existing rating equation is classified as Case 8. The new rating equations are calibrated based on the available measurements. However, two of the twenty two measurements were outliers. The average relative error for the new rating equation, based on twenty measurements, is 0.03%, with the relative errors ranging from -7.28% to 7.87%. The new rating, based on the twenty measurements, has 90% of calculated flows within 5% of the measured discharges and 100% within 10% of the measured discharges which improves the rating to good.

An assessment of impact of the new rating on historical data was performed using Flow Trace (a software application developed in-house). The average percent change between the existing and the new flow rating equations is 2.66% for the period from October 2001 through January 2004.

It is recommended that two to three additional stream flow data be used every two years to evaluate the performance of the rating. If the result of such an evaluation warrants, the rating equation needs to be recalibrated using seven to twelve additional field flow measurements.

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LIST OF ABBREVIATIONS AND ACRONYMS

DBHYDRO	Hydrometeorologic and Water Quality Database
OMD	Operations and Maintenance Department
Qmeas	Database tables 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
WCA	Water Conservation Area

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RATING ANALYSIS FOR PUMP STATION G310

1. Introduction

The structure G310 is located at the south corner of Stormwater Treatment Area 1 West (STA-1W) approximately 400 feet east and 1,500 feet north of the southeast corner of Section 34, Township 44 South, Range 39 East in Palm Beach County, Florida (Figure 1) (OMD, 2002). It is equipped with six pumps of three different capacities, with a total capacity of 3,040 cfs. G310 has two electric pumps with a combined discharge capacity of 200 cfs, two diesel pumps, with a combined discharge capacity of 940 cfs, and two diesel pumps with a combined discharge capacity of 1,900 cfs (Abtew et al, 2002). The structure is positioned immediately west of the Arthur R. Marshall Loxahatchee National Wildlife Refuge, also known as Water Conservation Area 1 (WCA-1).

G310 serves as the primary outflow pump station for STA-1W. It works in concert with the existing pump station G251 to pump treated agricultural drainage water, from which nutrients have been removed by STA-1W, to WCA1. Under high flow conditions, some of the eastern flow-way water is conveyed through structures G259, G258, G309 and G308 into the Discharge Canal and to WCA-1 via the G310 outflow pump station. Control of water levels in the collection canal by G310 also provides seepage control to isolate areas west of STA-1W from water levels in the treatment cells (OMD, 2002).

This report summarizes the rating analysis performed for G310. Section 2 outlines the objective and scope for the rating analysis at G310. 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 respectively. Development of a new flow rating 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 conclusions and recommendations respectively.

2. Objective and Scope

The objective of this discharge rating analysis is to evaluate the existing rating equations and look into possibilities of developing a new rating equation and improving the flow estimation accuracy for this pump station. The existing rating equation for G310 is classified as Case 8. The existing rating equation was developed based on the principles of energy conservation and the pump affinity laws. In this study, the equation is calibrated using the available measurements and pump performance curves provided by the manufacturer. This report presents estimation of flow computation errors in relation to field measurements for the existing as well as for the new flow rating equations.

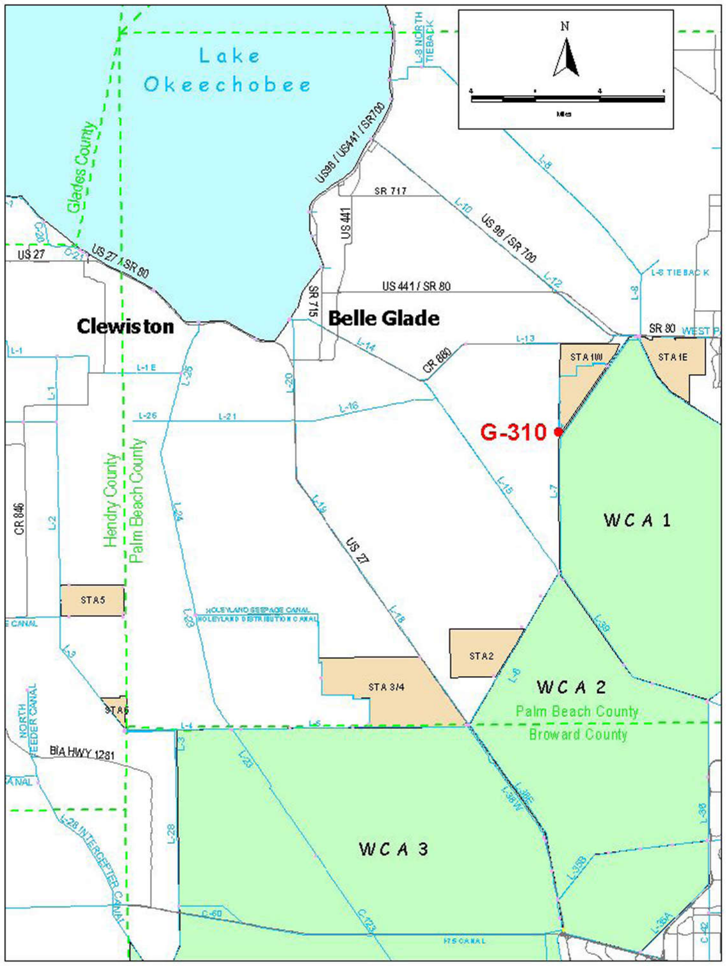

Figure 1. Location map for pump station G310

3. Stream Flow Measurements

3.1 Available Measurements

G310 is a six-unit pump station. Units 1 and 2 are constant-speed pumps and units 3 through 6 are variable-speed pumps. There were twenty two stream flow measurements for this station in the streamgauging records at the time of this analysis. The available measurements for pump station G310 were obtained by running structured query language (SQL) scripts shown in Appendix A and all the records are shown in Appendix B. The available measurements were divided into three groups according to the pump type and design flow. Group 1 includes two constant 100 cfs pumps, group 2 includes two variable 470 cfs pumps, and group 3 includes two variable 950 cfs pumps. The measured discharge per unit was determined based on the total number of pumps operating at the time of measurement for each group. 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 G310.

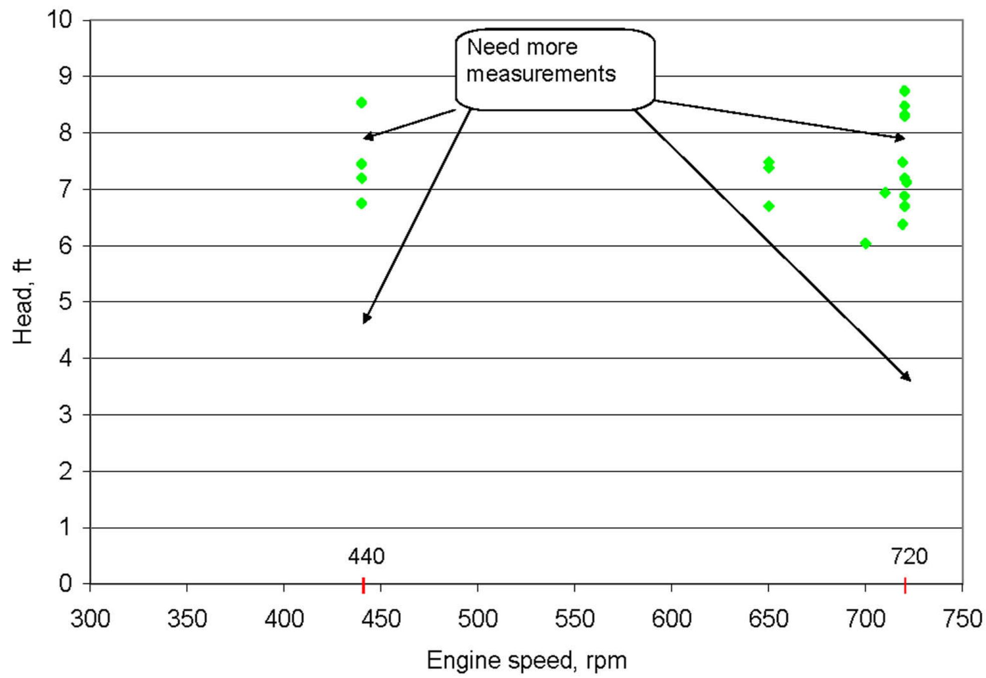

Figure 2. Flow measurements at various head and engine speed combinations for G310

3.2 Additional Measurements Required

There are two different design engine speeds for G310, 440 rpm for constant pumps and 720 rpm for variable pumps. The engine speeds of the available measurements range from 440 rpm to 720 rpm. The historical maximum and minimum values for headwater and tailwater elevations were obtained from hydrometeorologic and water quality database (DBHYDRO). The possible maximum and minimum head differentials were estimated based on the maximum and minimum values of headwater and tailwater elevations 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 pump station G310 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. The design engine speeds are also shown on Figure 2 (marked red in color). Table 3 is the summary of the available and required additional measurements for G310.

Table 1. Maximum and minimum stages for pump station G310

Station	Stage	Maximum		Minimum	
		Value	Date	Value	Date
G310_P	Headwater	11.2	2-Aug-03	6.01	6-Feb-04
	Tailwater	17.63	26-Oct-01	12.85	6-Feb-04
	Head differentials	11.62		0	

Table 2. Streamgauging needs for pump station G310

Range of Head Differential, ft	Range of Operation, rpm (RPM)		
	400≤RPM≤517	517<RPM<633	633≤RPM≤750
0.0≤DIFF≤5.7	5*	5*	5*
5.7<DIFF≤8.3	2**	5*	0
8.3<DIFF≤11	4**	5*	0

Note: * first priority, ** second priority

Table 3. Available and required additional measurements for pumps at G310

Pump Station	Design Engine Speed (rpm)	Range of Head Differential (ft)	Measurements		
			RPM	Available	Required
G310_P	Electric: 440	0.0≤DIFF≤5.7	440		5
		5.7<DIFF≤8.3	440	3	2
		8.3<DIFF≤11.0	440	1	4
G310_P	Diesel 470-cfs: 720	0.0≤DIFF≤5.7	720		5
		5.7<DIFF≤8.3	650≤RPM≤720	6	1
		8.3<DIFF≤11.0	720	1	4
G310_P	Diesel 950-cfs: 720	0.0≤DIFF≤5.7	720		5
		5.7<DIFF≤8.3	700≤RPM≤720	8	1
		8.3<DIFF≤11.0	720	3	2

4. Existing Flow Rating Equation

Pumps at G310 are, for flow calculation purposes, classified as Case 8 (DBHYDRO), for which the discharge is a function of the head and the engine speed. The brief descriptions provided here were taken from Rating Analysis for Pump Station S9 (Imru, 2003). In Case 8, the flow equations were developed from the principle of conservation of energy and pump affinity laws and are given by

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

where, Q is the discharge in cfs; N_0 is the design engine speed and N is the field engine speed; A, B, and C are regression coefficients; and H (ft) is the head differential.

The existing flow coefficients were taken from DBHYDRO and given in Table 4.

Table 4. Flow coefficients for pumps at G310 in Case 8 for the existing rating equation

Station	Unit No.	N_0	A	B	C	D=2C-1
G310_P	1	440	105.27	-0.00182	3.3	5.6
G310_P	2	440	105.27	-0.00182	3.3	5.6
G310_P	3	720	591.91	-3.14	1.58	2.16
G310_P	6	720	591.91	-3.14	1.58	2.16
G310_P	4	720	1218.95	-8.37	1.45	1.9
G310_P	5	720	1218.95	-8.37	1.45	1.9

Table 5 shows discharges calculated using the existing flow estimation method based on the headwater, tailwater, and engine speed obtained from the streamgauging database (Qmeas) table. The last column in Table 5 shows the estimated discharges from the existing equations for G310.

Table 5. Existing flow estimation at G310 using streamgauging data

DATE	TIME	HW	TW	$Q_{measured}$	N	H	$Q_{computed}$
5-Feb-02	15:40	9.18	16.38	81.0	440	7.20	104.0
10-Oct-01	11:47	8.69	17.23	86.5	440	8.54	103.1
25-Feb-03	10:49	9.47	16.22	88.0	440	6.75	104.3
24-Sep-02	8:08	9.27	16.72	89.0	440	7.45	103.9
10-Oct-00	12:21	9.14	17.88	480.0	720	8.74	495.4
18-Oct-00	9:27	9.12	17.42	508.0	720	8.30	503.0
26-Jul-02	10:57	9.11	16.24	519.5	721	7.13	523.0
16-Sep-02	10:36	10.08	16.78	532.0	720	6.70	528.5
16-Sep-02	12:04	10.08	16.78	450.0	650	6.70	455.3
24-Sep-02	9:35	9.28	16.76	451.0	650	7.48	440.3
6-Jun-03	9:56	9.14	15.52	535.5	719	6.38	532.2
10-Oct-00	11:43	9.4	17.88	1011	720	8.48	1033.2
18-Oct-00	10:42	8.68	17.43	1012	720	8.75	1024.6
18-Sep-01	13:06	8.7	17.02	873	720	8.32	1038.3
18-Jul-02	10:34	9.28	16.76	1108	719	7.48	1062.0
22-Jul-02	11:58	9.27	16.47	1080	720	7.20	1072.4
26-Jul-02	9:28	9.32	16.2	1085.4	720	6.88	1081.8
12-Aug-02	11:53	9.22	16.16	1113.5	710	6.94	1059.4
24-Sep-02	10:46	9.38	16.76	930	650	7.38	916.0
6-Jun-03	11:15	9.55	15.59	1091	700	6.04	1065.3
31-Jul-03	8:37	9.42	16.24	1150	720	6.82	1083.5

5. Evaluation of Existing Flow Equation

The existing flow rating equation for G310 is developed based on the principle of conservation energy and pump affinity laws. It is a standard rating equation and has been used to estimate the discharges through pumps at G310 in the Flow program since those pumps came on line.

There are twenty two 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 equations.

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 model and the results are shown in Table 6.

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

No.	Date	Time	HW	TW	Qmeasured	Qcomputed	Relative error
1	10-Oct-00	11:43	9.4	17.88	1011	1033.2	2.20%
2	10-Oct-00	12:21	9.14	17.88	960	990.8	3.21%
3	18-Oct-00	9:27	9.12	17.42	1016	1006.0	-0.99%
4	18-Oct-00	10:42	8.68	17.43	2024	2049.2	1.24%
5	18-Oct-00	12:12	8.14	17.48	2754	3152.1	14.46%
6	18-Sep-01	13:06	8.7	17.02	1746	2076.5	18.93%
7	10-Oct-01	11:47	8.69	17.23	173	206.2	19.21%
8	5-Feb-02	15:40	9.18	16.38	162	208.1	28.45%
9	18-Jul-02	10:34	9.28	16.76	1108	1062.0	-4.15%
10	22-Jul-02	11:58	9.27	16.47	1080	1072.4	-0.70%
11	26-Jul-02	9:28	9.32	16.2	1085.4	1081.8	-0.33%
12	26-Jul-02	10:57	9.11	16.24	1039	1046.0	0.67%
13	12-Aug-02	11:53	9.22	16.16	2227	2118.8	-4.86%
14	16-Sep-02	10:36	10.08	16.78	1064	1057.0	-0.66%
15	16-Sep-02	12:04	10.08	16.78	900	910.6	1.17%
16	24-Sep-02	8:08	9.27	16.72	178	207.8	16.74%
17	24-Sep-02	9:35	9.28	16.76	902	880.5	-2.38%
18	24-Sep-02	10:46	9.38	16.76	930	916.0	-1.50%
19	25-Feb-03	10:49	9.47	16.22	176	208.6	18.50%
20	6-Jun-03	9:56	9.14	15.52	1071	1064.4	-0.61%
21	6-Jun-03	11:15	9.55	15.59	1091	1065.3	-2.36%
22	31-Jul-03	8:37	9.42	16.24	1150	1083.5	-5.78%
Minimum Relative Error Value:							-5.78%
Maximum Relative Error Value:							28.45%
Average of relative errors							4.57%
Average of absolute relative errors							6.78%
95% Lower Confidence Interval for the Mean:							0.97%
95% Upper Confidence Interval for the Mean:							8.16%
Distribution of Absolute Relative Errors:							
Percentage of data with Absolute Relative Error <= 5% is: (Rating is very good)							68.18%
Percentage of data with 5% < Absolute Relative Error <= 10% is: (Rating is good)							4.55%
Percentage of data with 10% < Absolute Relative Error <= 15% is: (Rating is fair)							4.55%
Percentage of data with Absolute Relative Error > 15% is: (Rating is poor)							22.73%
Number of Records Retrieved from Database:							22
Number of Records with Valid Flow Estimates:							22

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 -5.78% to 28.45 %

and the average relative error is 4.57% for all the measurements. The absolute relative errors 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 results of errors per range of operation are used to determine whether the existing rating equation for pump station G310 can be improved or not.

Table 7. Absolute error per range of operation for G310

Range of Head Differential, ft (DIFF)	Range of Operation, rpm (RPM)				
	400≤RPM≤517	517<RPM<633	633≤RPM≤750	Abs Error (%)	
				Mean	Max
3.0≤DIFF≤5.7	–	–	–	–	–
5.7<DIFF≤8.3	21.23	–	2.01	5.93	28.45
8.3<DIFF≤11.0	19.21	–	8.01	8.6	19.21
Mean	20.72	–	3.68	6.82	–

6. Determination of Need for Improvement

Based on the existing stream flow measurements, the relative errors in discharge were obtained by comparison of measured and computed discharges for the existing rating equations (Table 6). Data verification results are reported in terms of relative errors that help 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 discharge, "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 percentage of data with absolute relative errors within 15% of the measured discharge is 72% (less than 95%); The Qmr results in Table 7 show that the absolute errors are higher at the lower range of operation (between 440 and 517 rpm). Overall, even though the average absolute relative error (6.78%) is less than 10%, the results from comparison between measured and computed discharges and results of errors per range of operation show that the existing rating has room for improvement, especially for the lower range of operation. A new calibration of the rating equation will be essential for better flow estimation accuracy at the lower operation range.

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 G310. Figures 3 and 4 show the head-discharge relationship for flows through the pumps at G310 under laboratory conditions for 470 cfs and 950 cfs pumps at 720 rpm. As shown in Figures 3 and 4, at the design flow capacity, the pump efficiency reaches the maximum point. 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 G310.

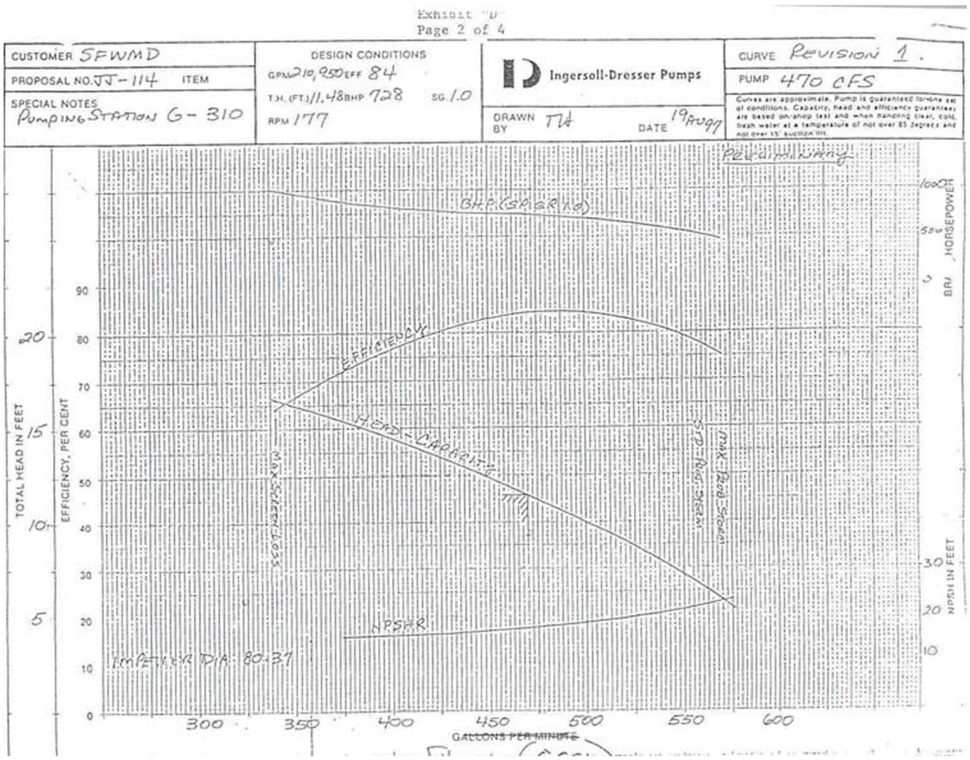

Figure 3. Performance curves for pumps at G310 for design flow 470 cfs

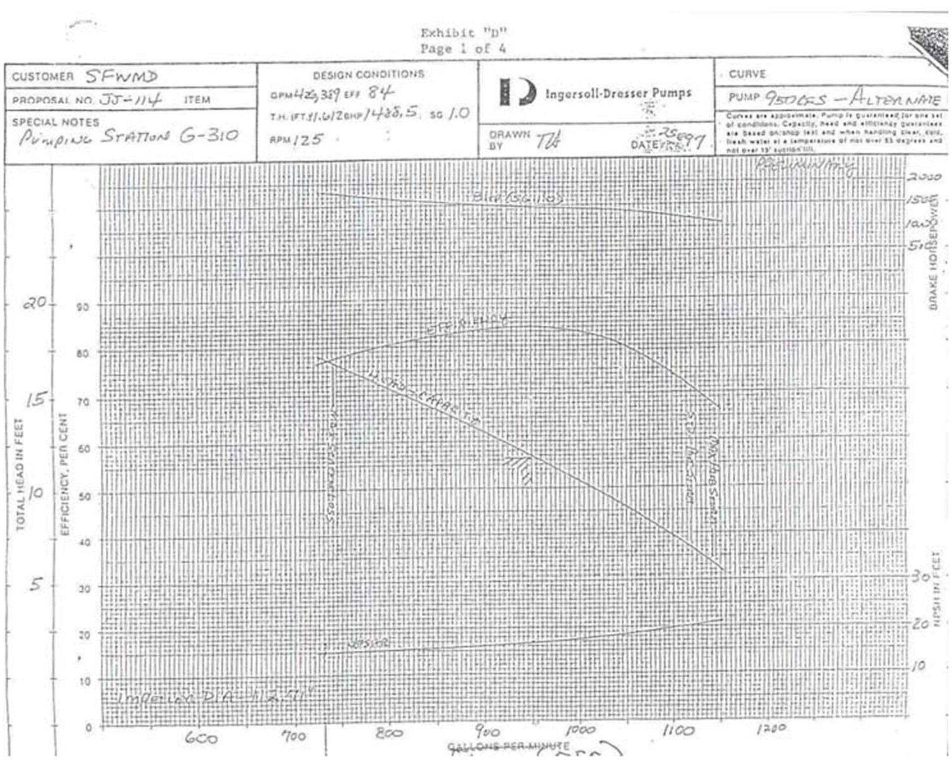

Figure 4. Performance curves for pumps at G310 for design flow 950 cfs

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. The absolute value of the hydraulic head differential (H) is used in all subsequent equations. On the basis of this concept Equation (2) is valid for all Q and H values for the rated pump speed (Imru and Wang, 2003).

$$Q_o = f(H) = A + BH_0^{\,C} \tag{2}$$

In Equation (2), 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.

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

$$\frac{Q}{Q_0} = \frac{N}{N_0} \tag{3}$$

Substituting Equation (2) into Equation (3) and rearranging, we obtain Equation (4).

$$Q = \frac{N}{N_0}(A + BH_0^{\,C}) \tag{4}$$

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

$$H_0 = \left[\frac{N_0}{N}\right]^2 H \tag{5}$$

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

$$Q = A\left[\frac{N}{N_0}\right] + BH^C\left[\frac{N_0}{N}\right]^{2C-1} \tag{6}$$

where: Q = Discharge (cfs)
N = Field Measured Engine Speed (rpm)
N_0= Design Engine Speed (rpm)
H = Field Measured Head Differential (ft)
A, B, C = Calibration Rating Coefficients

Equation (6) presents a model based on physical laws that can be used to estimate flow through pumps. This equation describes the relationship between discharge, head differential, and engine speed. Equation (6) will be calibrated to estimate flow for G310.

8. Calibration of the New Flow Rating Equation

Once the calibration field data points have been obtained, a rating analysis is performed to develop a flow equation for the selected pump station. The available measurements and pump performance curves as well as the affinity laws are used to perform the new rating analysis. The discharge at the rated engine speed can be obtained from the field data using the pump affinity laws if needed. The regression coefficients of Equation (2) 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 our goal becomes one of finding a method such that

$$F = \sum_{i=1}^{n} \left(\left(A + BH_0^{\ C}\right) - Q_0\right)^2 = \text{ minimum} \tag{7}$$

The expanded form of above equation is given by

$$F = \sum_{i=1}^{n} \left(Q_0^{\ 2} - 2AQ_0 - 2BH_0^{\ C}Q_0 + A^2 + 2ABH_0^{\ C} + B^2H_0^{\ 2C}\right) \tag{8}$$

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 similar as given below

$$\frac{\partial F}{\partial A} = \frac{\partial F}{\partial B} = \frac{\partial F}{\partial C} = \sum_{i=1}^{n} \left(2A + 2BH_0^{\ C} - 2Q_0\right) = 0 \tag{9}$$

$$B = \frac{\sum_{i=1}^{n} Q_0 - nA}{\sum_{i=1}^{n} H_0^{\ C}} \tag{10}$$

where n is the total number of measurements.

A starting estimation value 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 (10) 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 G310 are tabulated in Appendix B. Since calibration is based on good field data, it is necessary to analyze all the measured flows before doing calibration. In this case, two measurements were considered as outliers and discarded for the following reasons:

1. Three different types of pump operating at the same time. It causes errors in determining the measured discharge per unit.

2. The measured flow per unit is too low compared to the data from the pump performance curve. For example, the measured flow per unit on September 18, 2001 is 873 cfs at head 8.32 ft and the expected flow from the pump curve is 1065 cfs at the same head.

The detailed information for the outlier points is shown in Table 8.

Table 8. Data analysis for outliers for G310

DATE	TIME	HW (ft)	TW (ft)	Q (cfs)	PUMP#	PUMPDIA	N (rpm)	Comments
18-Oct-00	12:12	8.14	17.48	2754	2	3	720	This measurement operates three different capacity pumps. The engine speed for pump two is wrong (720)
18-Oct-00	12:12	8.14	17.48	2754	3	8	720	
18-Oct-00	12:12	8.14	17.48	2754	4	10	720	
18-Oct-00	12:12	8.14	17.48	2754	5	10	720	
18-Oct-00	12:12	8.14	17.48	2754	6	8	720	
18-Sep-01	13:06	8.7	17.02	1746	4	10	720	The measured flow per unit is too low
18-Sep-01	13:06	8.7	17.02	1746	5	10	720	

The two outlier points from the streamgauging tables were checked. Headwater, tailwater, and engine speed data obtained from DCVP (breakpoint flow inputs) were compared against values from streamgauging tables. As shown in Table 9, the streamgauging record data does not match the data from DCVP break point flow input for the outlier points. The discrepancies may be because of recording errors in stage, engine speed, and the total number of operating pumps.

Table 9. Comparison of streamgauging data and data from DCVP (breakpoint flow input) for outliers

DATE	TIME	PUMP#	Data from streamgauging flow				Data from DCVP			
			HW	TW	$Q_{measured}$	N	HW	TW	$Q_{computed}$	N
18-Oct-00	12:12	2	8.14	17.48	2754	720				
18-Oct-00	12:12	3	8.14	17.48	2754	720	7.92	17.48	2960	720
18-Oct-00	12:12	4	8.14	17.48	2754	720	7.92	17.48	2960	720
18-Oct-00	12:12	5	8.14	17.48	2754	720	7.92	17.48	2960	720
18-Oct-00	12:12	6	8.14	17.48	2754	720	7.92	17.48	2960	720
18-Sep-01	13:06	4	8.70	17.02	1746	720	8.76	17.02	2080	720
18-Sep-01	13:06	5	8.70	17.02	1746	720	8.76	17.02	2080	720

For pump station G310, after discarding two outliers, the remaining twenty measurements were used to calibrate the new rating equation (6). The rated flows (Q_0) and heads (H_0) at the design speed were calculated according to the pump affinity laws and shown in Table 10 for the remaining measurements.

Table 10. Rated flow and head at G310 for the remaining measurements

No.	DATE	TIME	HW	TW	$Q_{measured}$	N	H	$Q_0=Q(N_0/N)$	$H_0=H(N_0/N)^{\wedge 2}$
1	5-Feb-02	15:40	9.18	16.38	81.0	440	7.20	81.0	7.20
2	10-Oct-01	11:47	8.69	17.23	86.5	440	8.54	86.5	8.54
3	25-Feb-03	10:49	9.47	16.22	88.0	440	6.75	88.0	6.75
4	24-Sep-02	8:08	9.27	16.72	89.0	440	7.45	89.0	7.45
5	10-Oct-00	12:21	9.14	17.88	480.0	720	8.74	480.0	8.74
6	18-Oct-00	9:27	9.12	17.42	508.0	720	8.30	508.0	8.30
7	26-Jul-02	10:57	9.11	16.24	519.5	721	7.13	518.8	7.11
8	16-Sep-02	10:36	10.08	16.78	532.0	720	6.70	532.0	6.70
9	16-Sep-02	12:04	10.08	16.78	450.0	650	6.70	498.5	8.22
10	24-Sep-02	9:35	9.28	16.76	451.0	650	7.48	499.6	9.18
11	6-Jun-03	9:56	9.14	15.52	535.5	719	6.38	536.2	6.40
12	10-Oct-00	11:43	9.4	17.88	1011	720	8.48	1011.0	8.48
13	18-Oct-00	10:42	8.68	17.43	1012	720	8.75	1012.0	8.75
14	18-Jul-02	10:34	9.28	16.76	1108	719	7.48	1109.5	7.50
15	22-Jul-02	11:58	9.27	16.47	1080	720	7.20	1080.0	7.20
16	26-Jul-02	9:28	9.32	16.2	1085.4	720	6.88	1085.4	6.88
17	12-Aug-02	11:53	9.22	16.16	1113.5	710	6.94	1129.2	7.14
18	24-Sep-02	10:46	9.38	16.76	930	650	7.38	1030.2	9.06
19	6-Jun-03	11:15	9.55	15.59	1091	700	6.04	1122.2	6.39
20	31-Jul-03	8:37	9.42	16.24	1150	720	6.82	1150.0	6.82

Table 11 shows the values of coefficients and powers determined from regression analysis for the new rating equation. The values of the coefficient B are negative as long as the headwater is lower than the tailwater. This is consistent with the concept that pump discharge is lower when working against a positive static head (Imru and Wang, 2003).

Table 11. New rating equation coefficients and exponents for G310

Station	Unit No.	N_0	A	B	C	D=2C-1
G310_P	1	440	105	-0.34	2	3
G310_P	2	440	105	-0.34	2	3
G310_P	3	720	592	-1.3	2	3
G310_P	6	720	592	-1.3	2	3
G310_P	4	720	1220	-2.4	2	3
G310_P	5	720	1220	-2.4	2	3

Equation (11) presents the new rating equation for estimating flow through units 1 and 2 at G310, Equation (12) represents units 3 and 6, and Equation (13) represents units 4 and 5.

$$Q = 105\left[\frac{N}{N_0}\right] - 0.34H^{2.0}\left[\frac{N_0}{N}\right]^{3.0} \tag{11}$$

$$Q = 592\left[\frac{N}{N_0}\right] - 1.3H^{2.0}\left[\frac{N_0}{N}\right]^{3.0} \tag{12}$$

$$Q = 1220\left[\frac{N}{N_0}\right] - 2.4H^{2.0}\left[\frac{N_0}{N}\right]^{3.0} \tag{13}$$

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

Table 12 shows the results of comparing measured and computed discharges using the new model for pumps at G310.

Table 12. Comparison of measured and computed discharges for the new model

DATE	TIME	HW	TW	$Q_{measured}$	N	H	$Q_{computed\ new}$	Relative error new
5-Feb-02	15:40	9.18	16.38	81.0	440	7.20	87.4	7.87%
10-Oct-01	11:47	8.69	17.23	86.5	440	8.54	80.2	-7.28%
25-Feb-03	10:49	9.47	16.22	88.0	440	6.75	89.5	1.71%
24-Sep-02	8:08	9.27	16.72	89.0	440	7.45	86.1	-3.23%
10-Oct-00	12:21	9.14	17.88	480.0	720	8.74	492.7	2.65%
18-Oct-00	9:27	9.12	17.42	508.0	720	8.30	502.4	-1.09%
26-Jul-02	10:57	9.11	16.24	519.5	721	7.13	527.0	1.45%
16-Sep-02	10:36	10.08	16.78	532.0	720	6.70	533.6	0.31%
16-Sep-02	12:04	10.08	16.78	450.0	650	6.70	455.1	1.14%
24-Sep-02	9:35	9.28	16.76	451.0	650	7.48	435.6	-3.42%
6-Jun-03	9:56	9.14	15.52	535.5	719	6.38	538.0	0.47%
10-Oct-00	11:43	9.4	17.88	1011	720	8.48	1047.4	3.60%
18-Oct-00	10:42	8.68	17.43	1012	720	8.75	1036.3	2.40%
18-Jul-02	10:34	9.28	16.76	1108	719	7.48	1083.5	-2.21%
22-Jul-02	11:58	9.27	16.47	1080	720	7.20	1095.6	1.44%
26-Jul-02	9:28	9.32	16.2	1085.4	720	6.88	1106.4	1.93%
12-Aug-02	11:53	9.22	16.16	1113.5	710	6.94	1082.5	-2.78%
24-Sep-02	10:46	9.38	16.76	930	650	7.38	923.7	-0.67%
6-Jun-03	11:15	9.55	15.59	1091	700	6.04	1090.8	-0.02%
31-Jul-03	8:37	9.42	16.24	1150	720	6.82	1108.4	-3.62%
Average error								0.03%
Standard deviation								3.27%
Minimum error								-7.28%
Maximum error								7.87%

Figures 5, 6, and 7 show head-discharge relationships for G310 resulting from field measurements, existing model, and the new rating equations for pumps 1 & 2, 3 & 6, and 4 & 5 respectively. The continuous curves (Figures 6 & 7) represent the manufacturer's pump curves at 720 rpm. The squares (red in color) represent the 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 equations. As shown in Figures 6 and 7, the slopes of the curves from the new rating equations resemble those of the manufacturer's curves.

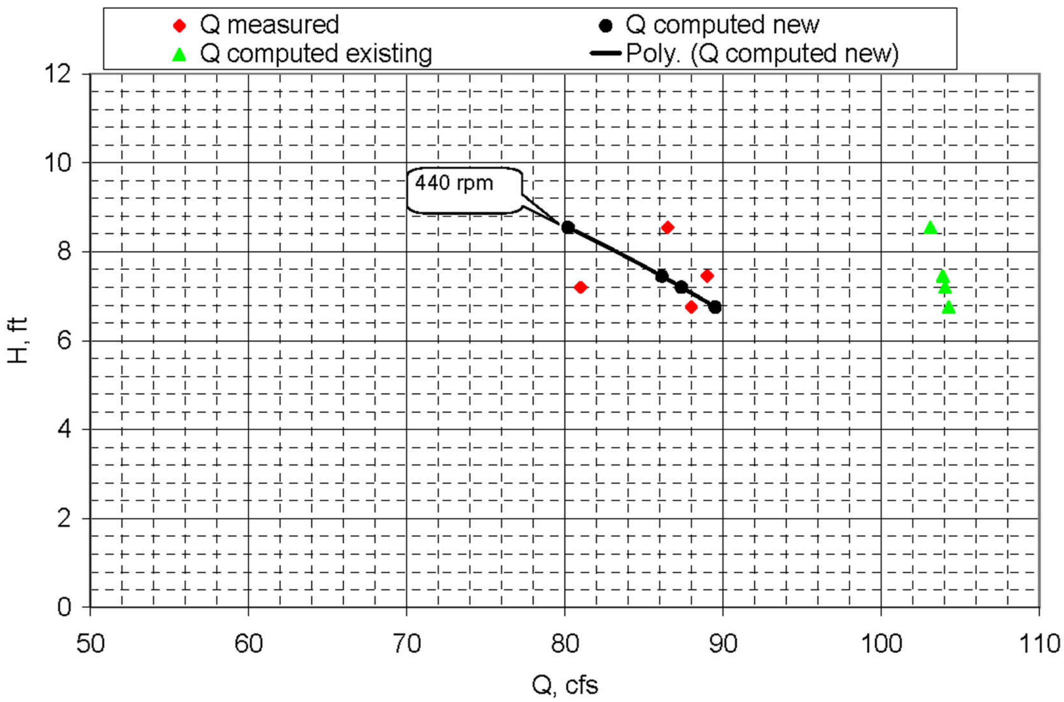

Figure 5. Head and discharge relationship for pumps 1 & 2 at G310 resulting from field measurements, existing model, and new rating equation

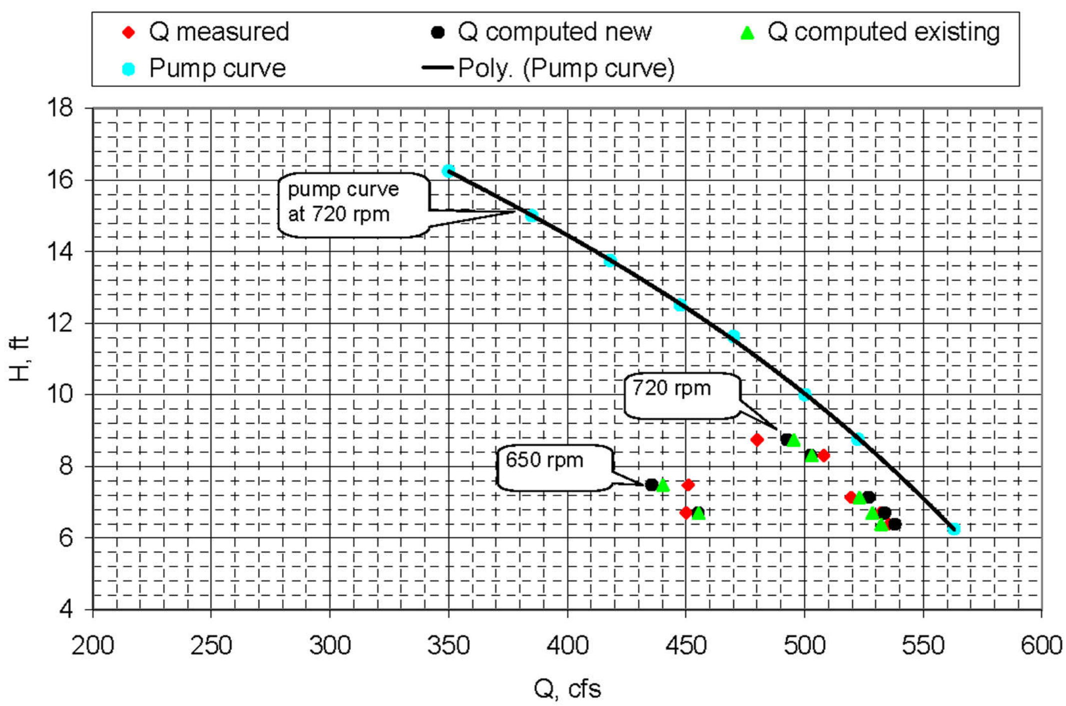

Figure 6. Head and discharge relationship for pumps 3 & 6 at G310 resulting from field measurements, existing model, and new rating equation

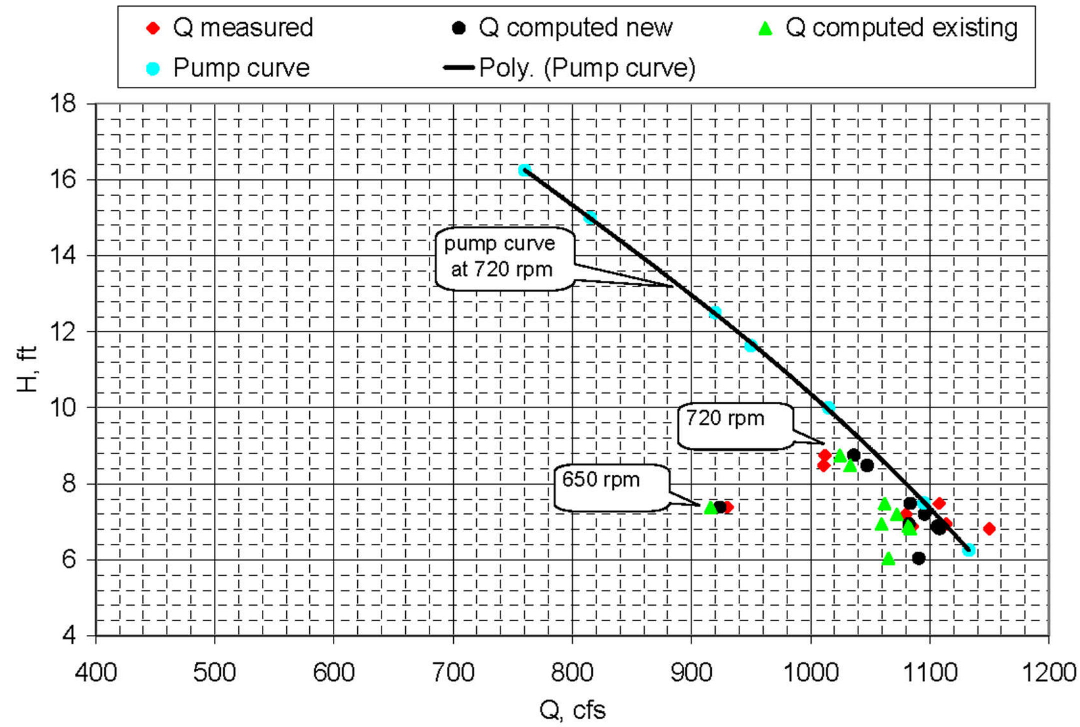

Figure 7. Head and discharge relationship for pumps 4 & 5 at G310 resulting from field measurements, existing model, and new rating equation

Table 13 shows the relative errors of computed discharges for pumps 1 & 2 using new and existing rating equations. The comparison results for pumps 3 & 6, and 4 & 5 are shown in Tables 14 and 15 respectively. As shown in Table 13, the averages of absolute relative errors are 5.02% and 20.72% for the new and existing rating equations respectively. The new rating equation (11) gives good flow estimates for pumps 1 & 2 at G310. The average absolute relative errors are similar using new and existing rating equations for pumps 3 &6, and 4 & 5.

Table 13. Comparison of relative errors of computed discharges for pumps 1 & 2

No.	Date	Head	Q measured	New rating equation			Existing rating equation		
				Q computed	Relative error	Absolute error	Q computed	Relative error	Absolute error
1	5-Feb-02	7.2	81	87.4	7.87%	7.87%	104.0	28.45%	28.45%
2	10-Oct-01	8.54	87	80.2	-7.28%	7.28%	103.1	19.21%	19.21%
3	25-Feb-03	6.75	88	89.5	1.71%	1.71%	104.3	18.50%	18.50%
4	24-Sep-02	7.45	89	86.1	-3.23%	3.23%	103.9	16.74%	16.74%
	Average error				-0.23%	5.02%		20.72%	20.72%
	Standard deviation				6.53%	3.02%		5.25%	5.25%
	Minimum error				-7.28%	1.71%		16.74%	16.74%
	Maximum error				7.87%	7.87%		28.45%	28.45%

Table 14. Comparison of relative errors of computed discharges for pumps 3 & 6

No.	Date	Head	Q measured	New rating equation			Existing rating equation		
				Q computed	Relative error	Absolute error	Q computed	Relative error	Absolute error
1	10-Oct-00	8.74	480	492.7	2.65%	2.65%	495.4	3.21%	3.21%
2	18-Oct-00	8.3	508	502.4	-1.09%	1.09%	503.0	-0.99%	0.99%
3	26-Jul-02	7.13	519.5	527.0	1.45%	1.45%	523.0	0.67%	0.67%
4	16-Sep-02	6.7	532	533.6	0.31%	0.31%	528.5	-0.66%	0.66%
5	16-Sep-02	6.7	450	455.1	1.14%	1.14%	455.3	1.17%	1.17%
6	24-Sep-02	7.48	451	435.6	-3.42%	3.42%	440.3	-2.38%	2.38%
7	6-Jun-03	6.38	535.5	538.0	0.47%	0.47%	532.2	-0.61%	0.61%
	Average error				0.21%	1.50%		0.06%	1.39%
	Standard deviation				1.97%	1.14%		1.81%	1.01%
	Minimum error				-3.42%	0.31%		-2.38%	0.61%
	Maximum error				2.65%	3.42%		3.21%	3.21%

Table 15. Comparison of relative errors of computed discharges for pumps 4 & 5

No.	Date	Head	Q measured	New rating equation			Existing rating equation		
				Q computed	Relative error	Absolute error	Q computed	Relative error	Absolute error
1	10-Oct-00	8.48	1011	1047.4	3.60%	3.60%	1033.2	2.20%	2.20%
2	18-Oct-00	8.75	1012	1036.3	2.40%	2.40%	1024.6	1.24%	1.24%
3	18-Jul-02	7.48	1108	1083.5	-2.21%	2.21%	1062.0	-4.15%	4.15%
4	22-Jul-02	7.2	1080	1095.6	1.44%	1.44%	1072.4	-0.70%	0.70%
5	26-Jul-02	6.88	1085.4	1106.4	1.93%	1.93%	1081.8	-0.33%	0.33%
6	12-Aug-02	6.94	1113.5	1082.5	-2.78%	2.78%	1059.4	-4.86%	4.86%
7	24-Sep-02	7.38	930	923.7	-0.67%	0.67%	916.0	-1.50%	1.50%
8	6-Jun-03	6.04	1091	1090.8	-0.02%	0.02%	1065.3	-2.36%	2.36%
9	31-Jul-03	6.82	1150	1108.4	-3.62%	3.62%	1083.5	-5.78%	5.78%
	Average error				0.01%	2.08%		-1.80%	2.57%
	Standard deviation				2.52%	1.22%		2.73%	1.92%
	Minimum error				-3.62%	0.02%		-5.78%	0.33%
	Maximum error				3.60%	3.62%		2.20%	5.78%

The overall relative errors of computed discharges using new and existing equations are calculated and shown in Table 16 for G310. As shown in Table 16, the average relative error for the new rating equation is 0.03%, with the relative errors ranging from -7.28% to 7.87%. For the existing rating equation, the average relative error is 3.35%, with the relative errors ranging from -5.78% to 28.45%. The average of absolute relative errors is 2.46% and 5.79% for the new and existing rating equations respectively.

The percentage of data within selected ranges of the measured discharge are calculated and shown in Table 17. As shown in Table 17, the new rating equation has 90% of calculated flows within 5% of the measured discharges and 100% within 10% while the existing rating equation has 75% of calculated flows within 5% of the measured discharges and 80% within 10% of the measured discharges.

Table 16. Relative errors of computed discharges using new and existing rating equations

No.	Date	Head	Q measured	New rating equation			Existing rating equation		
				Q computed	Relative error	Absolute error	Q computed	Relative error	Absolute error
1	5-Feb-02	7.2	81	87.4	7.87%	7.87%	104.0	28.45%	28.45%
2	10-Oct-01	8.54	86.5	80.2	-7.28%	7.28%	103.1	19.21%	19.21%
3	25-Feb-03	6.75	88	89.5	1.71%	1.71%	104.3	18.50%	18.50%
4	24-Sep-02	7.45	89	86.1	-3.23%	3.23%	103.9	16.74%	16.74%
5	10-Oct-00	8.74	480	492.7	2.65%	2.65%	495.4	3.21%	3.21%
6	18-Oct-00	8.3	508	502.4	-1.09%	1.09%	503.0	-0.99%	0.99%
7	26-Jul-02	7.13	519.5	527.0	1.45%	1.45%	523.0	0.67%	0.67%
8	16-Sep-02	6.7	532	533.6	0.31%	0.31%	528.5	-0.66%	0.66%
9	16-Sep-02	6.7	450	455.1	1.14%	1.14%	455.3	1.17%	1.17%
10	24-Sep-02	7.48	451	435.6	-3.42%	3.42%	440.3	-2.38%	2.38%
11	6-Jun-03	6.38	535.5	538.0	0.47%	0.47%	532.2	-0.61%	0.61%
12	10-Oct-00	8.48	1011	1047.4	3.60%	3.60%	1033.2	2.20%	2.20%
13	18-Oct-00	8.75	1012	1036.3	2.40%	2.40%	1024.6	1.24%	1.24%
14	18-Jul-02	7.48	1108	1083.5	-2.21%	2.21%	1062.0	-4.15%	4.15%
15	22-Jul-02	7.2	1080	1095.6	1.44%	1.44%	1072.4	-0.70%	0.70%
16	26-Jul-02	6.88	1085.4	1106.4	1.93%	1.93%	1081.8	-0.33%	0.33%
17	12-Aug-02	6.94	1113.5	1082.5	-2.78%	2.78%	1059.4	-4.86%	4.86%
18	24-Sep-02	7.38	930	923.7	-0.67%	0.67%	916.0	-1.50%	1.50%
19	6-Jun-03	6.04	1091	1090.8	-0.02%	0.02%	1065.3	-2.36%	2.36%
20	31-Jul-03	6.82	1150	1108.4	-3.62%	3.62%	1083.5	-5.78%	5.78%
	Average error				0.03%	2.46%		3.35%	5.79%
	Standard deviation				3.27%	2.07%		9.41%	8.08%
	Minimum error				-7.28%	0.02%		-5.78%	0.33%
	Maximum error				7.87%	7.87%		28.45%	28.45%

Table 17. Percentages of data within selected error ranges compared to the measured discharges

Criterion on Absolute Relative Error	New Rating Equation	Existing Rating Equation
Percentage of data within 5% of measured discharge	90% (18*)	75% (15)
Percentage of data within 10% of measured discharge	100% (20)	80% (16)
Percentage of data within 15% of measured discharge		80% (16)

*Number of measurements out of 20 satisfying the criterion indicated in the first column

9. Impact Analysis

An assessment of impact of the new flow rating equation on historical data was performed using Flow Trace (a software application developed in-house) for the period from October 2001 through January 2004. Parameters used in the Flow Trace program are shown in Table 18 for the existing and the new flow rating equations. The input data of headwater, tailwater, and engine speed are the same in the Flow Trace program for the existing and the new flow rating equations. The change in discharge estimate follows that of the discharge coefficients shown in Table 18.

Table 18. Comparison of parameters used in the Flow Trace program

Parameter	Unit	Existing Value	New Value
COEF11	1	105.27	105
COEF12	1	-0.00182	-0.34
COEF13	1	3.3	2
COEF14	1	5.6	3
COEF11	2	105.27	105
COEF12	2	-0.00182	-0.34
COEF13	2	3.3	2
COEF14	2	5.6	3
COEF11	3	591.91	592
COEF12	3	-3.14	-1.3
COEF13	3	1.58	2
COEF14	3	2.16	3
COEF11	4	1218.95	1220
COEF12	4	-8.37	-2.4
COEF13	4	1.45	2
COEF14	4	1.9	3
COEF11	5	1218.95	1220
COEF12	5	-8.37	-2.4
COEF13	5	1.45	2
COEF14	5	1.9	3
COEF11	6	591.91	592
COEF12	6	-3.14	-1.3
COEF13	6	1.58	2
COEF14	6	2.16	3

Table 19 presents the impact of the new rating on historical flow data as obtained using the Flow Trace program. The existing flow column indicates the historical data obtained using the existing rating. The new flow column gives the discharge with the new discharge coefficients for pumps at G310. The monthly percent change in flow between existing and new flow rating equations is indicated in the last column in Table 19. The average of the monthly percent changes between the existing and the new flow rating equations is -2.66%.

Table 19. Comparison of the existing and new flow rating equation

Site I.D.	Statistic	Year	Month	New flow	Existing flow	Percent Change
13344391	MEAN	2001	Oct	879	881	-0.27%
13344391	MEAN	2001	Nov	198	207	-4.73%
13344391	MEAN	2001	Dec	0	0	0.00%
13344391	MEAN	2002	Jan	179	213	-16.18%
13344391	MEAN	2002	Feb	585	597	-2.10%
13344391	MEAN	2002	Mar	11	12	-7.82%
13344391	MEAN	2002	Apr	9	11	-11.85%
13344391	MEAN	2002	May	206	206	0.19%
13344391	MEAN	2002	Jun	940	931	0.99%
13344391	MEAN	2002	Jul	1046	1039	0.69%
13344391	MEAN	2002	Aug	1033	1025	0.81%
13344391	MEAN	2002	Sep	1035	1042	-0.73%
13344391	MEAN	2002	Oct	1132	1136	-0.32%
13344391	MEAN	2002	Nov	408	418	-2.28%
13344391	MEAN	2002	Dec	944	952	-0.80%
13344391	MEAN	2003	Jan	666	675	-1.42%
13344391	MEAN	2003	Feb	296	314	-5.52%
13344391	MEAN	2003	Mar	305	312	-2.22%
13344391	MEAN	2003	Apr	121	121	-0.26%
13344391	MEAN	2003	May	164	167	-1.57%
13344391	MEAN	2003	Jun	491	487	0.88%
13344391	MEAN	2003	Jul	161	164	-2.04%
13344391	MEAN	2003	Aug	1394	1393	0.06%
13344391	MEAN	2003	Sep	437	445	-1.65%
13344391	MEAN	2003	Oct	185	187	-1.32%
13344391	MEAN	2003	Nov	174	180	-3.42%
13344391	MEAN	2003	Dec	128	131	-2.32%
13344391	MEAN	2004	Jan	64	71	-9.34%
Minimum Percent Change						-16.18%
Maximum Percent Change						0.99%
Average Percent Change						-2.66%
Standard Deviation of Percent Change						4.10%

The new rating equation recalibrated here is based on physical laws and principles of hydraulics and show better rating results compared to the existing equation. The new rating equation shows an improvement over the existing one for pumps at G310, especially for the 100 cfs capacity units. The improvement warrants changing the discharge coefficients in the structure tables of the hydrologic database.

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 -2.66%. At the time of this rating analysis, the historical data produced using the existing flow rating equation are considered good and can continue to be used for the period before the effective date of the new flow rating equation.

10. Conclusions

The existing rating equation yields an average relative error of 3.35% with the relative errors ranging from -5.78% to 28.45%. It has 75% of calculated flows within 5% of the measured discharges and 80% within 10% of measured discharges. The existing rating equation can be classified as fair based on the existing criteria. However, with the new rating equation, the average relative error is 0.03% with the relative errors ranging from -7.28% to 7.87%. The new rating equation gives 90% of calculated flows within 5% of the measured discharges and 100% within 10% of the measured discharges, which improves the rating to good.

The new flow rating equation presented here estimates flow better than the existing one. The impact analysis results show that the historical data generated using the existing flow rating equation are considered good at the time of this rating analysis.

11. Recommendations

It is recommended that two to three additional stream flow data be used every two years to investigate the performance of the rating. When the result of such an investigation warrants, a recalibration of the rating needs to be done using seven to twelve additional field measurements.

Based on the flow data accuracy improvement that can be attained using the new flow rating equation as shown in Tables 13 through 16, it is recommended that the discharge coefficients for G310 in the database be changed to the new values provided in Table 18. However, according to the results of impact analysis, the historical flow records need not be changed.

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APPENDIX

APPENDIX A

SQL scripts for pump station G310

```
set pagesize 2500
set linesize 350
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, 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.q_meas_id = y.q_meas_id
and x.station = 'G310_P'
/
```

APPENDIX B

Available measurements for pumps at pump station G310

STATION	MEAS_DATE	TIME	HW	TW	UNITS	Q	PUMP#	CASE	PUMPDIA	N	NNOFLOW	T	UNIT
G310_P	10-Oct-00	11:43	9.4	17.88	6	1011	5	8	10	720	300	V	5
G310_P	10-Oct-00	12:21	9.14	17.88	6	960	3	8	8	720	300	V	3
G310_P	10-Oct-00	12:21	9.14	17.88	6	960	6	8	8	720	300	V	6
G310_P	18-Oct-00	9:27	9.12	17.42	6	1016	3	8	8	720	300	V	3
G310_P	18-Oct-00	9:27	9.12	17.42	6	1016	6	8	8	720	300	V	6
G310_P	18-Oct-00	10:42	8.68	17.43	6	2024	4	8	10	720	300	V	4
G310_P	18-Oct-00	10:42	8.68	17.43	6	2024	5	8	10	720	300	V	5
G310_P	18-Oct-00	12:12	8.14	17.48	6	2754	2	8	3	720	300	C	2
G310_P	18-Oct-00	12:12	8.14	17.48	6	2754	3	8	8	720	300	V	3
G310_P	18-Oct-00	12:12	8.14	17.48	6	2754	4	8	10	720	300	V	4
G310_P	18-Oct-00	12:12	8.14	17.48	6	2754	5	8	10	720	300	V	5
G310_P	18-Oct-00	12:12	8.14	17.48	6	2754	6	8	8	720	300	V	6
G310_P	18-Sep-01	13:06	8.7	17.02	6	1746	4	8	10	720	300	V	4
G310_P	18-Sep-01	13:06	8.7	17.02	6	1746	5	8	10	720	300	V	5
G310_P	10-Oct-01	11:47	8.69	17.23	6	173	1	8	3	440	300	C	1
G310_P	10-Oct-01	11:47	8.69	17.23	6	173	2	8	3	440	300	C	2
G310_P	5-Feb-02	15:40	9.18	16.38	6	162	1	8	3	440	300	C	1
G310_P	5-Feb-02	15:40	9.18	16.38	6	162	2	8	3	440	300	C	2
G310_P	18-Jul-02	10:34	9.28	16.76	6	1108	5	8	10	719	300	V	5
G310_P	22-Jul-02	11:58	9.27	16.47	6	1080	4	8	10	720	300	V	4
G310_P	26-Jul-02	9:28	9.32	16.2	6	1085.4	5	8	10	720	300	V	5
G310_P	26-Jul-02	10:57	9.11	16.24	6	1039	3	8	8	718	300	V	3
G310_P	26-Jul-02	10:57	9.11	16.24	6	1039	6	8	8	724	300	V	6
G310_P	12-Aug-02	11:53	9.22	16.16	6	2227	4	8	10	710	300	V	4
G310_P	12-Aug-02	11:53	9.22	16.16	6	2227	5	8	10	710	300	V	5
G310_P	16-Sep-02	10:36	10.08	16.78	6	1064	3	8	8	720	300	V	3
G310_P	16-Sep-02	10:36	10.08	16.78	6	1064	6	8	8	720	300	V	6
G310_P	16-Sep-02	12:04	10.08	16.78	6	900	3	8	8	650	300	V	3
G310_P	16-Sep-02	12:04	10.08	16.78	6	900	6	8	8	650	300	V	6
G310_P	24-Sep-02	8:08	9.27	16.72	6	178	1	8	3	440	300	C	1
G310_P	24-Sep-02	8:08	9.27	16.72	6	178	2	8	3	440	300	C	2
G310_P	24-Sep-02	9:35	9.28	16.76	6	902	3	8	8	650	300	V	3
G310_P	24-Sep-02	9:35	9.28	16.76	6	902	6	8	8	650	300	V	6
G310_P	24-Sep-02	10:46	9.38	16.76	6	930	4	8	10	650	300	V	4

STATION	MEAS_DATE	TIME	HW	TW	UNITS	Q	PUMP#	CASE	PUMPDIA	N	NNOFLOW	T	UNIT
G310_P	25-Feb-03	10:49	9.47	16.22	6	176	1	8	3	440	300	C	1
G310_P	25-Feb-03	10:49	9.47	16.22	6	176	2	8	3	440	300	C	2
G310_P	6-Jun-03	9:56	9.14	15.52	6	1071	3	8	8	719	300	V	3
G310_P	6-Jun-03	9:56	9.14	15.52	6	1071	6	8	8	719	300	V	6
G310_P	6-Jun-03	11:15	9.55	15.59	6	1091	4	8	10	700	300	V	4
G310_P	31-Jul-03	8:37	9.42	16.24	6	1150	4	8	10	720	300	V	4