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RATING ANALYSIS FOR PUMP STATION S13

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ACKNOWLEDGEMENTS

The authors wish to express appreciation to Charles Mercy, for clarifying the actual operation of the pumps at S-13 and the location of the speed sensors, and providing insight into the pump units' performances at different ranges of engine speeds and static heads.

DEFINITIONS

ADCP	Acoustic Doppler Current Profiler
NLIN	Nonlinear regression procedure in SAS software
TDH	Total dynamic head
TSH	Total static head
SFWMD	South Florida Water Management District
USGS	US Geological Survey

EXECUTIVE SUMMARY

A rating analysis of pump station S-13 was carried out using the conventional case 8 model. A new rating equation based on the pump unit performance curve was developed. The new rating is in good agreement with the pump station performance curve over the historical range of static heads and engine speeds. Additionally, this rating was compared to available stream flow measurements for validation purposes, but was not calibrated to them due to data quality and quantity limitations. It is recommended that the new rating equation be implemented in DBHYDRO.

An impact analysis was performed to evaluate the need to recompute historical flows through pump station S-13 for the period of record spanning 1992 trough 2009. During this process, it was detected that the static database and the current FLOW program do not accommodate the case of a pipe discharging into a horizontal plane, perpendicular to the main flow direction, as occurs with this pump station. Therefore, the actual calculations of both tailwater elevations and flows could be erroneous since 1992. A comparison between the archived flows and the flows computed using the existing rating equation along with corrected tailwater elevations showed that the historical mean daily flows were previously underestimated, on average, by 4.7 percent, and that the absolute error was approximately 5.1 percent. Hence, this problem should be addressed in HYDROEDIT and in the new version of the FLOW program. Additionally, mean daily flows were computed with the new equation and modified discharge pipe diameters that account for the discharge configuration mentioned previously. They were compared with the mean daily flows currently stored in DBHYDRO. The average absolute difference between the two sets of flows is about 6 percent. It is recommended that the historical flows be recomputed with the new rating equation and modified discharge pipe diameters, and reloaded into DBHYDRO.

1.0 INTRODUCTION

1.1 Background

The structure S-13 is a combination of a pumping station and a gated spillway. S-13 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 pumps each having a rated capacity of 180 cfs at a 4 ft static head.

The purpose of the structure is to release flood runoff from, prevent over drainage of, and prevent salt water intrusion into the agricultural area served by Canal 11 west of the structure. In particular, 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 as possible to the optimum elevation of 2.2 ft above mean sea level.

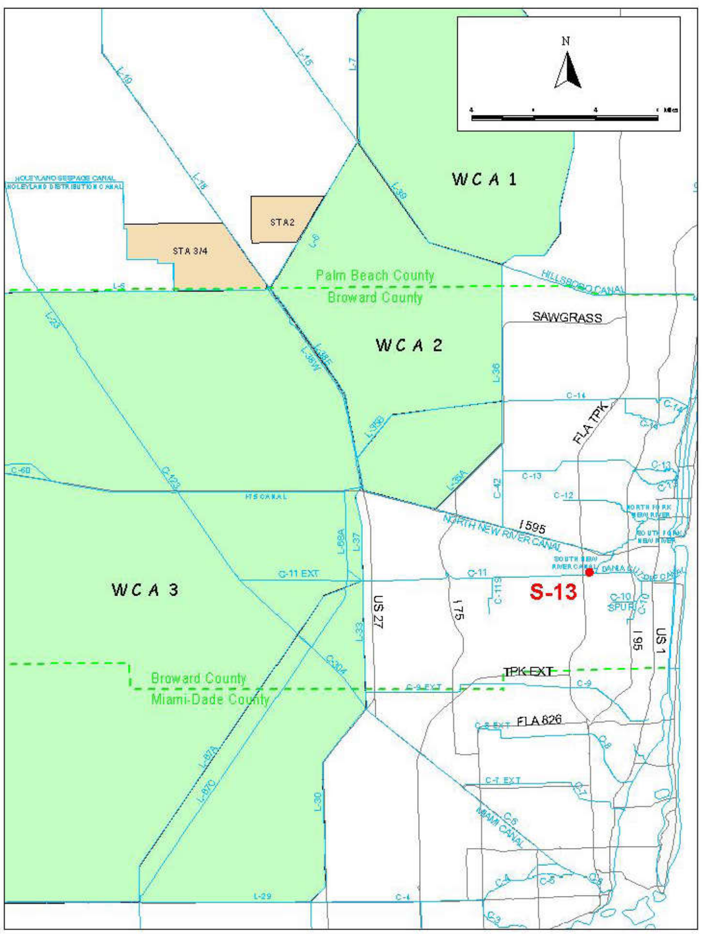

Figure 1. **Location map for pump station S13**

Pump operation takes place when the structure's 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 design discharge for the pumps is 540 cfs.

The annual flow records of structure S13 consist of flows through the spillway and flows through the pumps. The responsibility of flow monitoring through the spillway and pumps is divided between two agencies. Discharge computations through the spillway are carried out by the US Geological Survey (USGS) while the South Florida Water Management District (SFWMD) computes flow through the pumps.

1.2 Objectives and Scope

The purpose of the rating analysis conducted in this study is to improve upon the existing rating equation for the pumps at S-13. The new rating equation is based on pump performance characteristics and hydraulic properties of the pump station. Additionally, the new rating equation was compared to the existing rating equation along with available stream flow measurements.

2.0 STATION DESIGN

Cross sectional and plan views of the pump station design are shown in Figure 2. A detailed view of the discharge pipe extension is shown in Figure 3. These figures contain the record drawings completed just after the pump station was constructed in 1954. It is recommended that a new survey be conducted to verify the invert elevation and actual geometry at the outlet of the discharge pipes.

The station performance curves developed by the manufacturer are shown in Figure 4. It should be noted that these performance curves represent the relationship between discharge and total static head (TSH) (as opposed to total dynamic head, TDH). These curves were developed for a rated engine speed of 1200 rpm (e.g., the SFWMD structure book, the OMD 2002 Report and Imru and Wang, 2004), before the 1995 mechanical modifications were carried out. During the upgrade in 1995, only the engines and the reduction gears were replaced. All the piping was kept intact. Although the references cited earlier indicate that the design engine speed was increased from 1200 to 1625 rpm after the mechanical upgrade, the current engine tag specifies a design engine speed of 1800 rpm for each unit. Also specified is a gear reduction ratio of 9.42, resulting in a rated pump speed of 191 rpm (The actual design speed of the pump from the pump curve available shows that the design pump speed is 190.5 rpm, which if multiplied by the gear reduction ratio of 9.42, will result in a design engine speed of about 1800 rpm). This matches the design pump speed specified before the 1995 upgrade and confirms the fact that the pumps remained unchanged while the engines were replaced. Unless other mechanical modifications occurred between February 1995 and the present, the design engine speeds should be set to 1800.

The dimensions of the station piping are shown in Table 1 while Table 2 lists the appurtenances located between each pump and the discharge outlet. Listed also are the head loss coefficients. Table 3 contains estimates of pipe roughness for steel pipes.

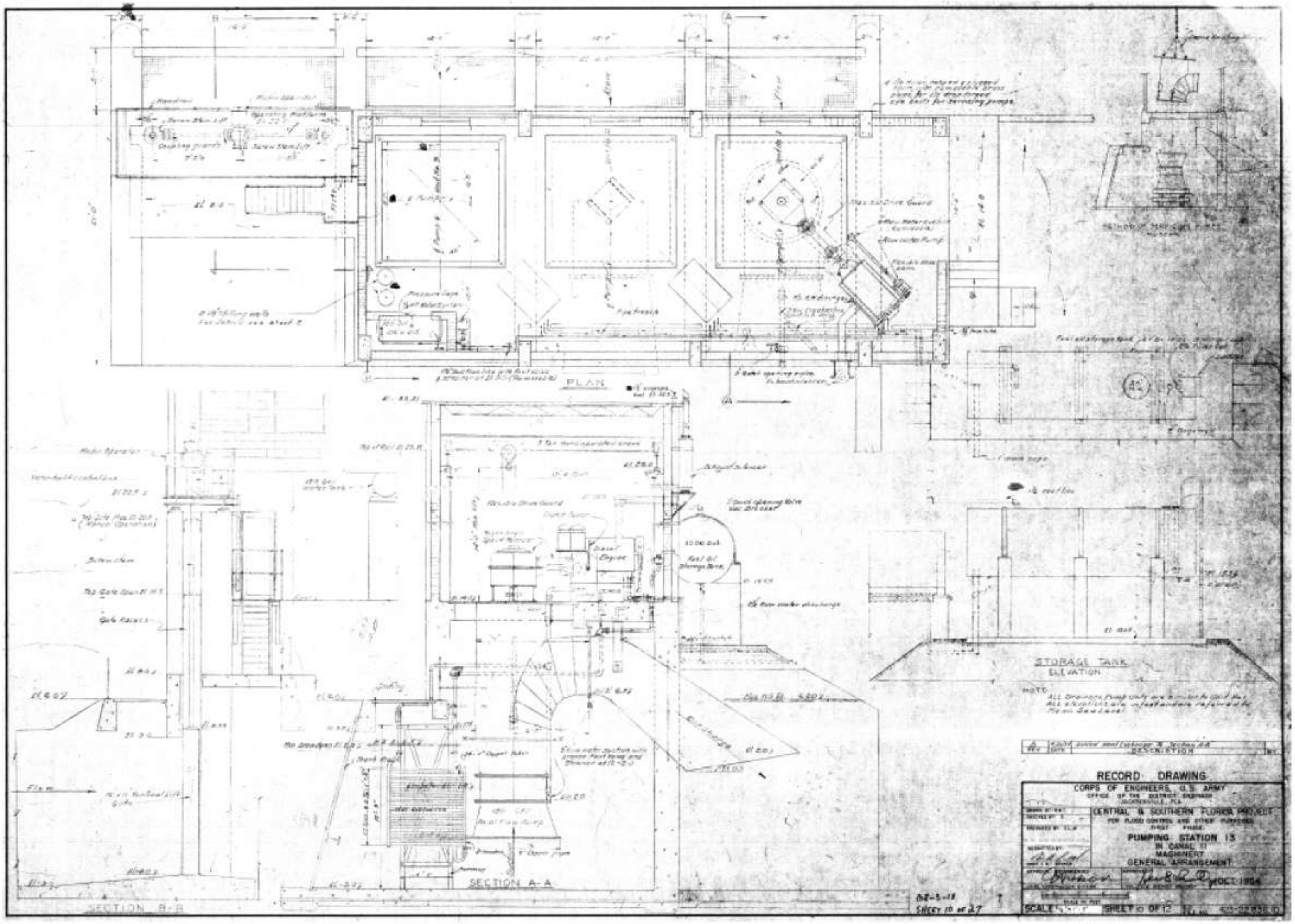

Figure 2. Plan and Profile Views of Pump Station S-13

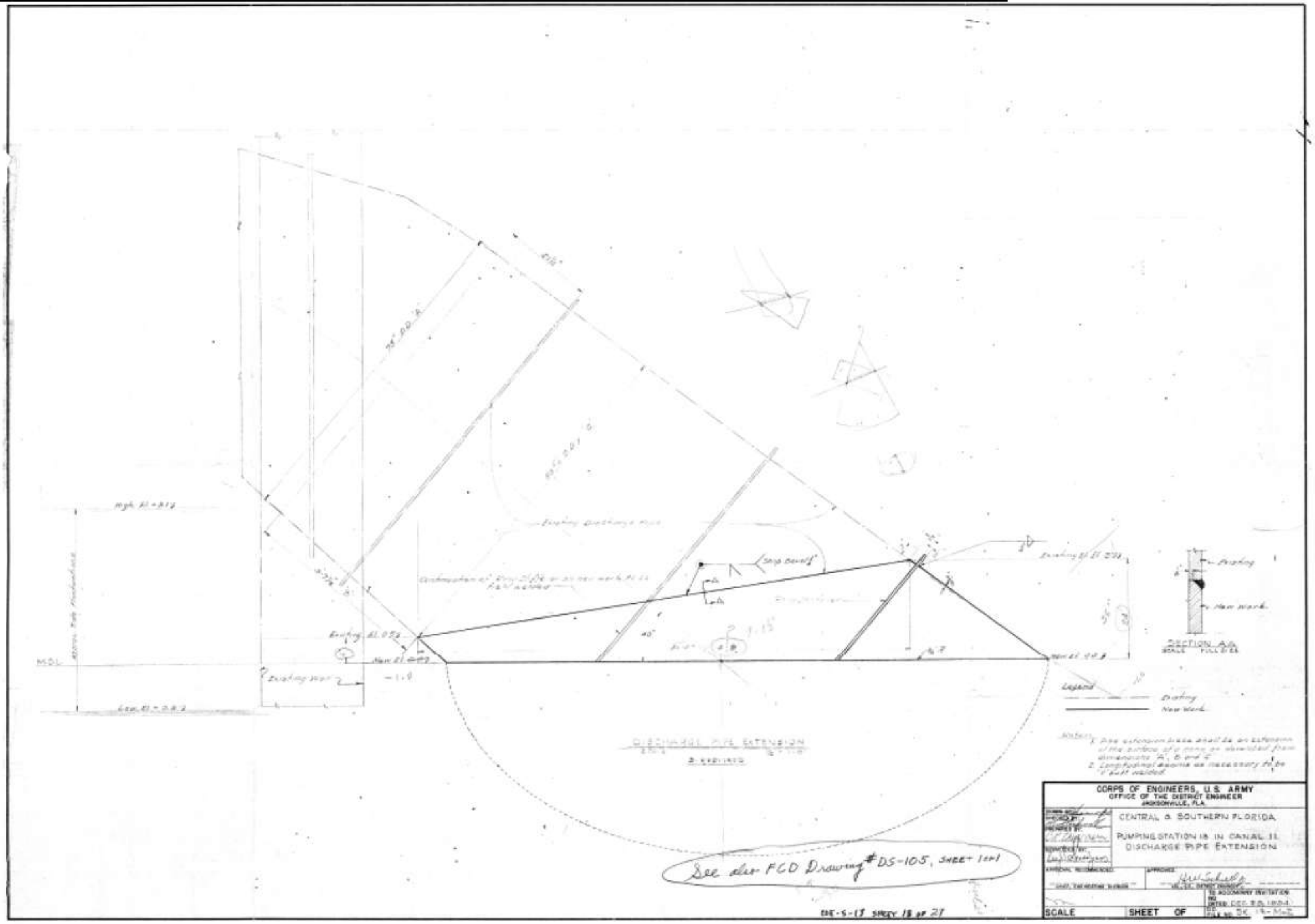

Figure 3. Discharge Pipe Extension at Pump Station S-13

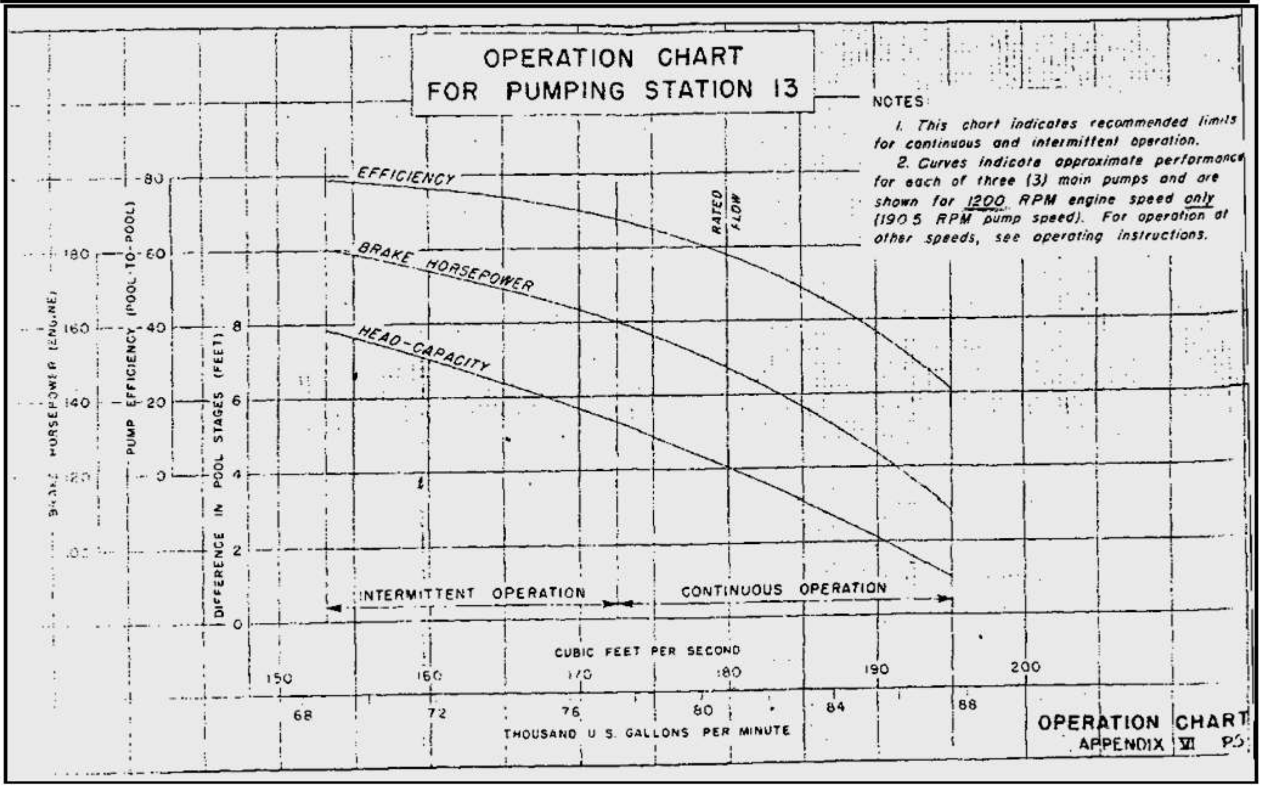

Figure 4. Pump Performance Curves

Table 1. Dimensions of the station piping at Pump Station S-13

Parameter	Value	Source
Pipe OD	80.6 in	As-builts
Wall Thickness	0.500 in	Jones et al. (2006)
Pipe Length	27.4 ft	As-builts
Area	32.34 ft^2	

Table 2. Pump Station Appurtenances and Local Head Loss Coefficients

Number	Type	Local Loss coefficient (K)		Source
		Minimum	Maximum	
1	Bellmouth entrance	0.04	0.07	Jones et al. (2006)
1	Expansion	0.012	0.012	Jones et al. (2006)
1	90° elbow	0.14	0.23	Jones et al. (2006)
1	Exit	1.00	1.00	Jones et al. (2006)
	Total	1.15	1.24	
	Total (geometric average)	1.20		

Table 3. Estimates of Pipe Roughness for Steel Pipes.

Steel Pipe Roughness ε (ft)	Type	Source
0.00015	new steel	Hydraulic Inst. (1990)
0.00133	old steel	Jones et al. (2006)

3.0 STREAM FLOW DATA

There are nineteen stream flow measurements for this station in the streamgauging database. Five of these measurements were performed with a Price AA Current Meter between 1991 and 1993, when the design engine speed was 1200 rpm. These measurements are presented in Table 4. The other fourteen measurements were collected with an Acoustic Doppler Current Profiler (ADCP) between 1997 and 1999, when the design engine speed was 1800 rpm. These flow measurements are shown in Table 5. In Tables 4 and 5, also shown are the static head, number of pumps in operation, average discharge, average engine speed and quality tag.

The static head is calculated as the difference between the effective tailwater elevation and the monitored headwater elevation at S13-H. The effective tailwater elevation is the maximum of the discharge pipe centerline elevation, 0.07 ft, and the monitored tailwater elevation at S13-T. For all the available measurements, the outlet flow was submerged.

With each flow measurement the quality tag or qualitative accuracy qualifier is presented. For this purpose, five categories of qualifiers were used: "excellent", "good", "fair", "poor", and "bad". There are some measurements that were not processed after the measurement, which is represented by the tag "N". It is not clear what criteria were used to assess the quality of these measurements. Also, no review of the data could be performed under the current District's quality assurance initiative for stream gauging data because these measurements were acquired with a software and methodology that are different from the ones currently in use and the field notes are not available.

In general, these flow measurements were obtained within a small total static head range of 0 to 2 ft. In this range of operation, the efficiency of each pump is below 40% and drops sharply with decreasing static head (see Figure 4). Also, in this range of operation cavitation might occur, which has the potential to cause performance degradation and permanent damage to the pump components and structure (Jones et al., 2006). In fact, for the design engine speed of 1800 rpm a great amount of vibration has been observed (Charles Mercy, personal communication). Thus, the pump performance may be less than expected and, consequently, the flow measurements may be of limited use for rating calibration.

Table 4. Price AA Current Meter Measured Flow Data

Measurement Date	Static Head (ft)	# Units in Operation	Average Discharge (cfs)	Average Engine Speed (rpm)	Quality Tag
4/5/1991	0.73	3	156	1050	Good
10/17/1991	0.11	2	163	1050	Bad
10/24/1991	1.60	2	146	1050	Good
10/7/1993	1.30	3	161	1002	Good
10/2/1991	1.73	3	110	750	Good

Table 5. ADCP Measured Flow Data

Measurement Date	Static Head (ft)	# Units in Operation	Average Discharge (cfs)	Average Engine Speed (rpm)	Quality Tag
6/23/1999	0.55	3	93	961	Fair
8/26/1999	0.61	3	121	1000	Not Processed
11/7/1998	1.37	3	99	1050	Not Processed
8/26/1999	0.58	3	121	1060	Good
6/15/1997	1.66	3	117	1200	Not Processed
1/15/1997	1.78	3	118	1227	Good
11/7/1998	1.40	3	131	1300	Not Processed
6/23/1999	0.50	3	140	1422	Fair
6/23/1999	0.87	3	148	1443	Fair
11/6/1998	0.47	3	164	1488	Bad
10/7/1996	0.81	3	171	1501	Fair
9/10/1995	0.08	3	180	1671	Bad
6/15/1997	1.62	3	169	1700	Not Processed
11/7/1998	1.12	3	169	1700	Not Processed

4.0 RATING ANALYSIS

4.1 Methodology

The approach implemented here for developing the rating equations reflects the procedure established previously by Imru and Wang (2003). The model rating equation is the Case 8 model:

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

where Q is the discharge at an engine or pump speed of N RPM, H is the total static head (TSH), No is the design engine or pump speed, and A, B and C are parameters determined through regression. The form of this expression was determined through dimensional analysis and is based on the pump affinity laws. For pumps driven by electric motors, No = N so the ratios involving these parameters are eliminated. Usually, the TSH versus Q relationship is 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. In this case, however, the TSH versus Q relationship for each installed pump was provided by the US Corps of Engineers (Figure 4). The station performance curve can sometimes be calibrated to available stream flow data. A nonlinear regression procedure is normally used to fit equation 1 to the performance curve.

4.2 Existing Rating Equations

The existing rating equation is based on the Case 8 model. This equation was developed by fitting equation (1) to the TSH versus Q relationship shown in Figure 4 with computed head losses subtracted from the ordinate values. In that effort, it appears that the TSH versus Q relationship was mistaken for the TDH versus Q relationship. Consequently, it is expected that the existing equation will underestimate discharges. The existing rating equation parameters A, B and C are 195.4,-3.1067, 1.2936 for a design speed of 1795 rpm.

4.3 New Rating Equation

The new rating equation was developed following the procedure discussed in Section 4.1. The nonlinear regression procedure NLIN of SAS was used to fit equation 1 to the pump station performance curve (Figure 4). The resultant regression parameters along with their approximate 95% confidence limits are presented in Table 6.

Table 6. Proposed Rating Equation Parameters

Regression Parameter for Equation (1)	Approximate lower 95% C.I.	Estimate	Approximate upper 95% C.I.
A	195.6	197.3	198.9
B	-3.2334	-2.4771	-1.7208
C	1.2531	1.3910	1.5290

Also, the TDH versus Q relationship for the design speed was determined by adding the head losses through the intake and discharge works to each point on the pump station performance curve (Figure 4). Additionally, the pump station performance curves for several engine speeds were determined through application of the affinity laws (see, for example, Jones et al. 2006) to the TDH versus Q relationship for the design speed. These curves were used to develop the pump station performance curves for different engine speeds assuming minimum, average and maximum head losses.

Figure 5 shows the pump station performance curve and the TDH vs. Q relationship (assuming average head loss) for the design engine speed along with the existing and proposed ratings. The associated head loss computations are provided in appendix A. The proposed rating equation computes flows to within 0.5% of the performance curve, while the existing rating equation underestimates the flows by as much as 2.4%.

Figure 6 depicts the available flow measurements performed with Price AA Current Meters along with the proposed rating curves for various engine speeds, when the design engine speed was 1200 rpm. There are three flow measurements acquired at 1050 rpm that are, on average, 10 percent lower than the flows computed with the proposed rating equation. On the other hand, the measurements collected at 1002 and 750 rpm show good agreement with the expected flows. Analogously, Figure 7 presents the flow measurements performed with the ADCP along with the pump station performance curves for different engine speeds based on a design speed of 1800 rpm. In this group of measurements there are two tagged "Bad", six tagged "Not Processed", four judged to be "Fair" and two judged to be "Good". The average absolute difference between the measured flows and the flows computed with the proposed rating equation is about 6 percent. Table 7 provides a comparison of the stream gauging data with the flows computed with the proposed rating equation. Ten flow measurements are below the projected values, with the major differences occurring for flows acquired at 961, 1422 and 1700 rpm. The rating is less accurate at lower speeds since these flows were computed by applying the affinity laws outside of the range where efficiency has minimal variation. Also, all the measured flows collected at 1700 rpm are biased low. Since one of these measurements was tagged "bad" and two have not been processed, there could be a problem with their accuracy. Also, for engine speeds close to 1800 rpm a great amount of vibration has been observed by the station operator, which can degrade the pump unit performance (see section 3). Therefore, it is difficult to judge whether there is a problem with the flow measurements or the rating analysis for this range of operation. On the other hand, there are four flow measurements, acquired at 1000, 1060, 1488 and 1501 rpm, whose values are larger than the flows computed with the proposed rating. While the pumps experience less vibrational problems at these speeds, there are some inaccuracies inherent to the computed flows due to the application of the affinity laws beyond the ideal range mentioned previously. These differences in behavior together with the lack of information about the accuracy of the flow measurements suggest that additional flow measurements are needed to calibrate the proposed rating, especially for higher static head values.

5.0 UNCERTAINTY ANALYSIS

No uncertainty analysis was carried out due to a lack of information regarding the source and magnitude of the errors associated with the manufacturer's pump unit performance curves. An uncertainty analysis could be performed in the future if more information on pump unit performance errors and more reliable stream gauging data become available.

6.0 SYSTEM OPERATION

For the each pump at S-13, the expected range of operating conditions can be estimated by reading from Figure 5 the expected range of discharges corresponding to the expected range of static heads over which pumping would typically occur. As an alternative, conventional system performance curves were computed for minimum, average and maximum head losses. These losses were based on minimum, average and maximum static heads of 0.00, 0.94, and 2.99 feet NGVD, respectively, acquired from historical data in DBHYDRO. These system curves along with the estimated pump performance curve (obtained by adding computed head losses to the pump unit curve supplied by the USACE) for the design engine speed are plotted in figure 8. Apparently, these pumps will discharge at rate somewhat greater the rated value of 180 cfs with velocities above 5.0 ft/s. The pump station operating characteristics shown in figure 8 indicate that the pumps will operate at points near the extreme right end of their performance curve, below the design point of operation. In this range of operation, the efficiency of the pumps is below 50 percent and drops sharply (Figure 4). Due to the vibration problems cited earlier, the pumps usually operate at a maximum engine speed of 1500 rpm, and only under extreme conditions they run at higher speeds (Charles Mercy, personal communication).

7.0 IMPACT ANALYSIS

In order to assess the need for recomputing historical flows, an impact analysis over the period of record spanning January 1, 1992 through August 6, 2009 was carried out. During this process, it was detected that neither the current framework of the static database nor the logic of the FLOW program considers the

Table 7. Comparison of the Flow Measurements with the Proposed Rating

Average Engine Speed (rpm)	Static Head (ft)	$Flow_{ADCP}$ (cfs)	$Flow_{rating}$ (cfs)	Flow Difference (%)
961	0.55	93	102	-10
1000	0.61	121	106	12
1050	1.37	99	105	-6
1060	0.58	121	113	6
1200	1.66	117	121	-4
1227	1.78	118	124	-5
1300	1.40	131	135	-4
1422	0.50	140	154	-11
1443	0.87	148	155	-5
1488	0.47	164	162	1
1501	0.81	171	162	5
1671	0.08	180	183	-2
1700	1.62	169	181	-7
1700	1.12	169	183	-9

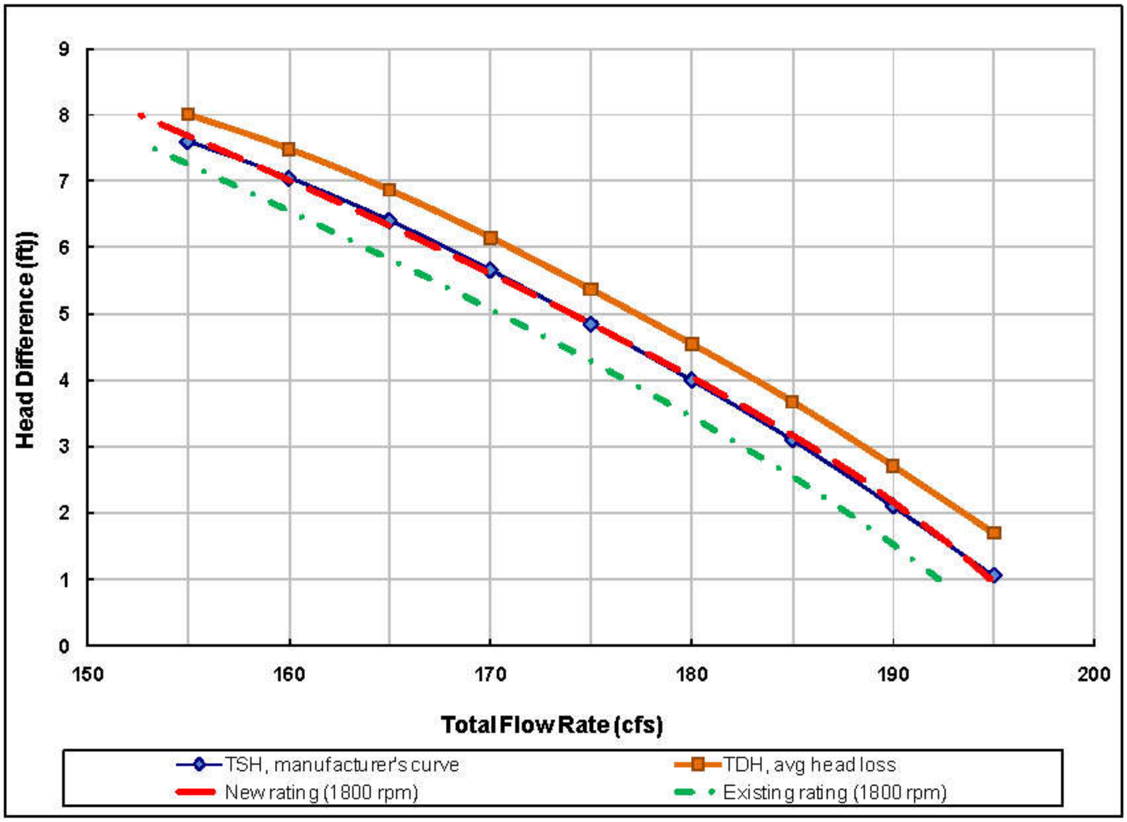

Figure 5. Station performance and rating curves for Pump Station S-13

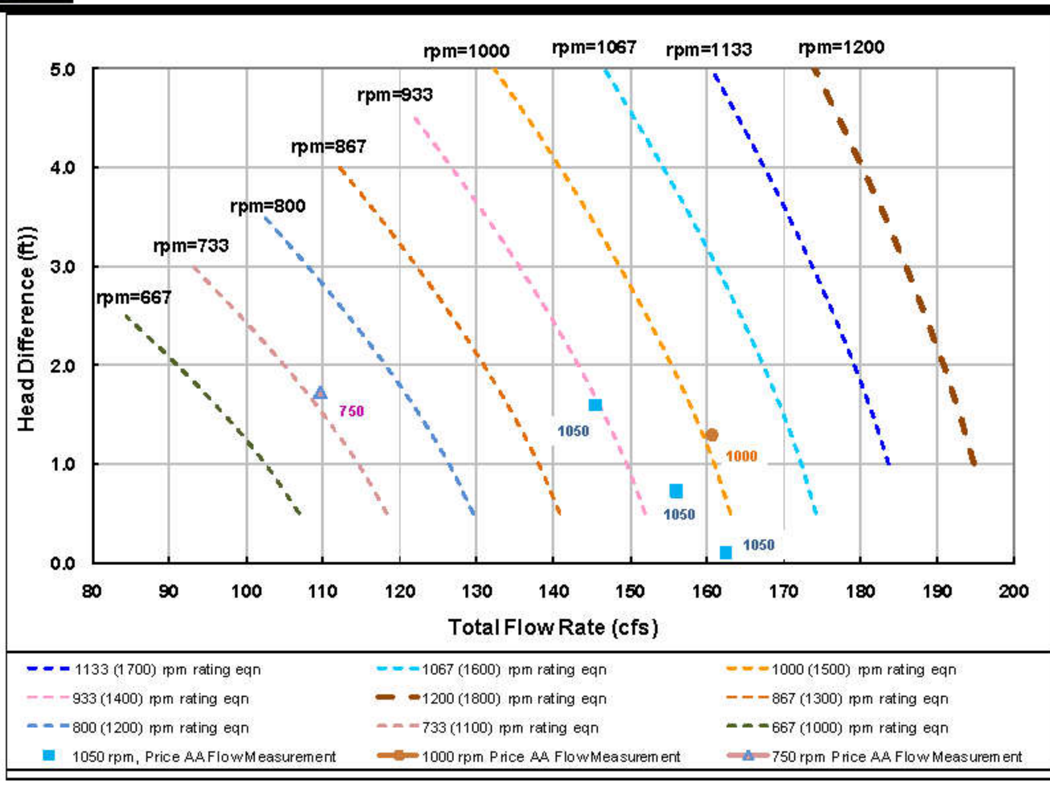

Figure 6. Proposed Rating and Price AA Flow Measurements

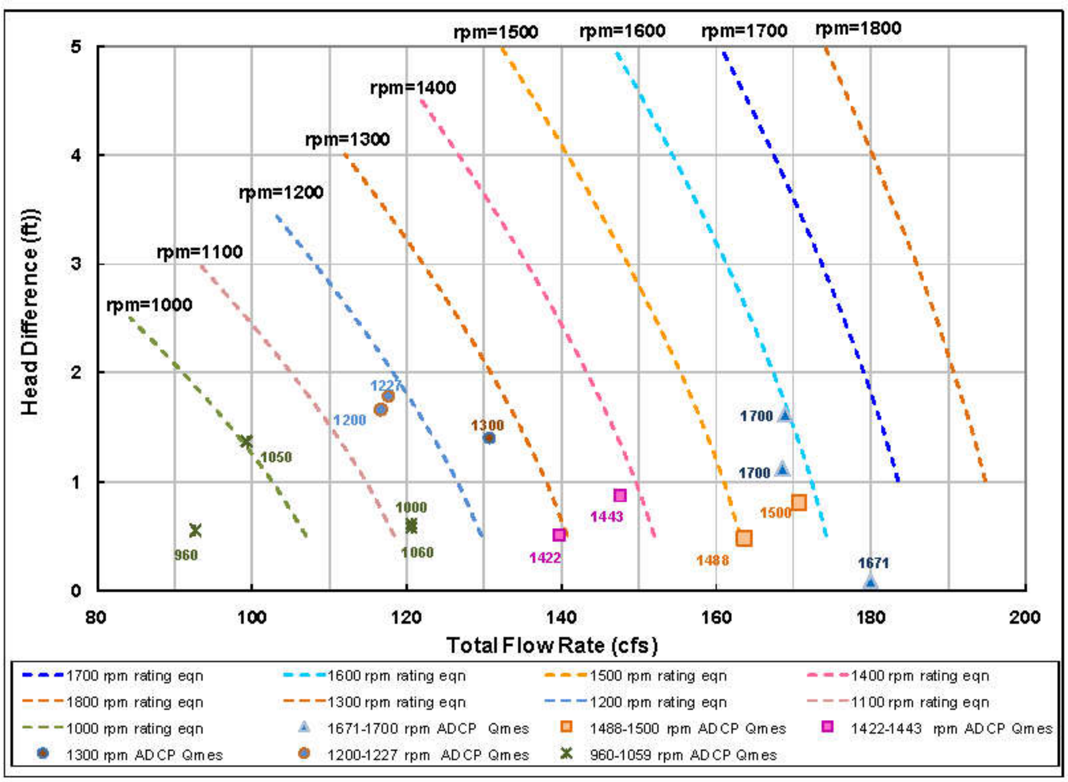

Figure 7. Proposed Rating and ADCP Flow Measurements

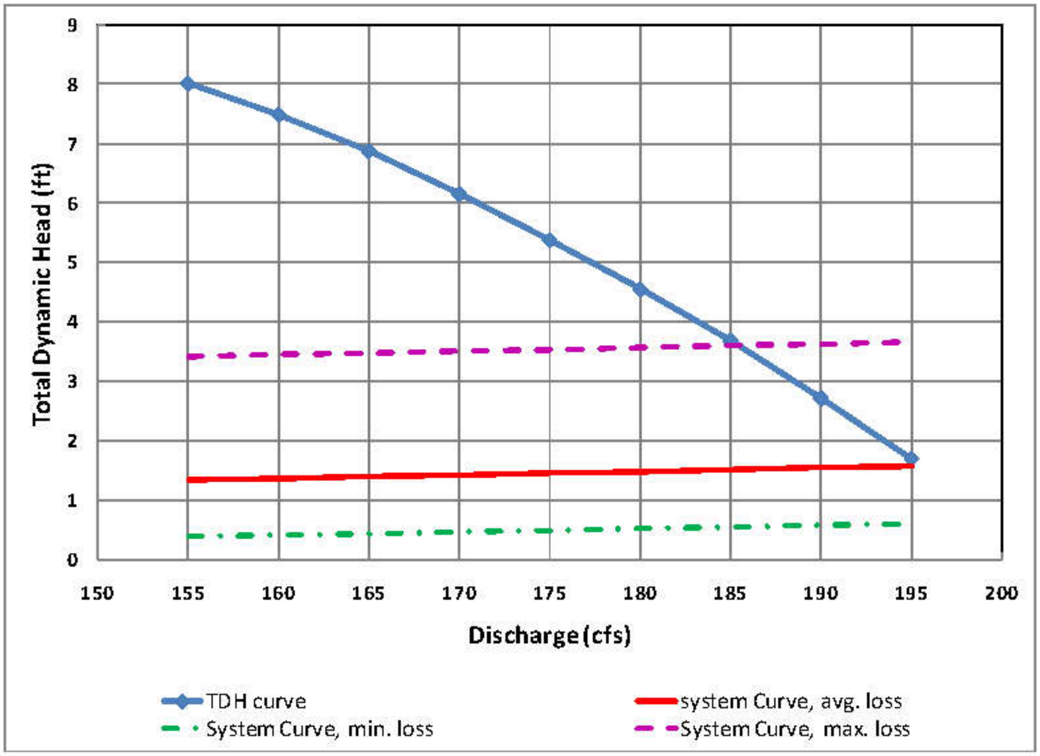

Figure 8. Operating Conditions at Pump Station S-13

case of a pipe discharging into a horizontal plane, perpendicular to the main flow direction, as occurs with this pump station (Figure 3). Therefore, the actual calculations of both tailwater elevations and flows could be erroneous. In order to analyze this problem, the pipe diameters were set to zero ft in the development static database, while the invert elevations were set to their actual value of zero ft. A comparison between the archived flows and the flows computed using the existing rating equation along with corrected tailwater elevations showed that the historical mean daily flows were previously underestimated, on average, by 4.7 percent, and that the absolute error was approximately 5.1 percent. Hence, the pipe diameters should be set equal to zero in the static database or the new FLOW program should be modified to include this type of outflow configuration. Additionally, a comparison between the archived flows and the flows computed with the new rating equation along with existing tailwater elevations showed that the archived flows were previously underestimated, on average, by 3.5 percent.

The final impact analysis involved the evaluation of the differences between existing archived flows, and, the flows computed with both the new rating equation and the modified pipe diameters. For the days when pumping occurred, the existing flows are, on average, about 5.2 percent lower than the proposed flows while the absolute average error is approximately 6.2 percent.

The Standard Operating Procedures for Flow Data Management in the District's Hydrologic Database (Akpoji et al, 2003) indicate that the historical record of computed flows is subject to modification if a new rating changes its flow volume by more than 5%. It is therefore recommended that the historical flows through S-13 that are stored in District databases be recomputed with the new rating equation and the revised pipe diameters.

8.0 STREAMGAUGING NEEDS

The stream gauging data needs for pump station S-13 are summarized in Table 8. Indicated is the desired number of flow measurements under each of the operating conditions.

Table 8. Stream Gauging Needs for Pump Station S-13

TSH (ft)	Number of measurements required at specified engine speed		
	650~1067 rpm	1068~1483 rpm	1484~1900 rpm
<0	5	5	4
0.0~1.0	4	4	4
1.0~2.0	4	3	5
2.0~4.0	5	5	5

9.0 SUMMARY AND CONCLUSIONS

A rating analysis of pump station S-13 was carried out using the conventional case 8 model. A new rating equation based on the pump unit performance curve was developed. The new rating is in good agreement with the pump station performance curve over the historical range of static heads and engine speeds. Additionally, this rating was compared to available stream flow measurements for validation purposes, but was not calibrated to them due to data quality and quantity limitations. It is recommended that the new rating equation be implemented in DBHYDRO.

An impact analysis was performed to evaluate the need to recompute historical flows through pump station S-13 for the period of record spanning 1992 trough 2009. During this process, it was detected that the static database and the current FLOW program do not accommodate the case of a pipe discharging into a horizontal plane, perpendicular to the main flow direction, as occurs with this pump station. Therefore, the actual calculations of both tailwater elevations and flows could be erroneous since 1992. A comparison between the archived flows and the flows computed using the existing rating equation along with corrected tailwater elevations showed that the historical mean daily flows were previously underestimated, on average, by 4.7 percent, and that the absolute error was approximately 5.1 percent. Hence, this problem should be addressed in HYDROEDIT and in the new version of the FLOW program. Additionally, mean daily flows were computed with the new equation and modified discharge pipe diameters that account for the discharge configuration mentioned previously. They were compared with the mean daily flows currently stored in DBHYDRO. The average absolute difference between the two sets of flows is about 6 percent. It is recommended that the historical flows be recomputed with the new rating equation and modified discharge pipe diameters, and reloaded into DBHYDRO.

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APPENDIX

Head Loss Calculations

Minimum head loss calculations

1800						Swamee & Jain (1976)				
TSH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Dynamic Head (ft)
7.60		155.00	4.49	2975158	0.31	0.01070	0.01	0.37	0.39	7.99
7.05		160.00	4.63	3071131	0.33	0.01067	0.01	0.40	0.41	7.46
6.41		165.00	4.77	3167103	0.35	0.01064	0.02	0.42	0.44	6.85
5.66		170.00	4.92	3263076	0.38	0.01061	0.02	0.45	0.46	6.12
4.85		175.00	5.06	3359049	0.40	0.01058	0.02	0.47	0.49	5.34
4.00		180.00	5.21	3455022	0.42	0.01056	0.02	0.50	0.52	4.52
3.10		185.00	5.35	3550995	0.44	0.01053	0.02	0.53	0.55	3.65
2.10		190.00	5.50	3646968	0.47	0.01051	0.02	0.56	0.58	2.68
1.05		195.00	5.64	3742940	0.49	0.01048	0.02	0.59	0.61	1.66

Maximum head loss calculations

1800						Swamee & Jain (1976)				
TSH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Dynamic Head (ft
7.60		155.00	4.49	2975158	0.31	0.01416	0.02	0.41	0.43	8.03
7.05		160.00	4.63	3071131	0.33	0.01415	0.02	0.44	0.45	7.50
6.41		165.00	4.77	3167103	0.35	0.01413	0.02	0.46	0.48	6.89
5.66		170.00	4.92	3263076	0.38	0.01412	0.02	0.49	0.51	6.17
4.85		175.00	5.06	3359049	0.40	0.01411	0.02	0.52	0.54	5.39
4.00		180.00	5.21	3455022	0.42	0.01411	0.02	0.55	0.58	4.58
3.10		185.00	5.35	3550995	0.44	0.01410	0.03	0.58	0.61	3.71
2.10		190.00	5.50	3646968	0.47	0.01409	0.03	0.61	0.64	2.74
1.05		195.00	5.64	3742940	0.49	0.01408	0.03	0.65	0.67	1.72

Average head loss calcuations

1800						$f_{av} = sqrt(f_{min}f_{max})$				
TSH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$h_l = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total Head Loss (ft)	Dynamic Head (ft)
7.60		155.00	4.49	2975158	0.31	0.01231	0.02	0.39	0.41	8.01
7.05		160.00	4.63	3071131	0.33	0.01229	0.02	0.42	0.43	7.48
6.41		165.00	4.77	3167103	0.35	0.01226	0.02	0.44	0.46	6.87
5.66		170.00	4.92	3263076	0.38	0.01224	0.02	0.47	0.49	6.15
4.85		175.00	5.06	3359049	0.40	0.01222	0.02	0.50	0.52	5.37
4.00		180.00	5.21	3455022	0.42	0.01220	0.02	0.53	0.55	4.55
3.10		185.00	5.35	3550995	0.44	0.01218	0.02	0.56	0.58	3.68
2.10		190.00	5.50	3646968	0.47	0.01217	0.02	0.59	0.61	2.71
1.05		195.00	5.64	3742940	0.49	0.01215	0.02	0.62	0.64	1.69