Flow Rating Analysis for Pump Station S-385

Nubbin Slough / New Palm Stormwater Treatment Area

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Executive Summary

A rating analysis of S-385 was carried out using the conventional case 8 model. Four rating equations were developed since up to four pumps can be operating in parallel and they discharge into a common force main. All four equations yield discharge rates that are within 0.6% of the discharges derived from the pump station rating curve under the expected range of static heads. Additionally, under the expected range of static heads, it was found that discharges can range from about 35 cfs with a single pump operating to about 136 cfs with all pumps operational. Given the uncertainties inherent to the hydraulic head loss calculations, it is recommended that the rating equations be recalibrated with measured flows. Because of the hydraulic conditions at the downstream end of the force main, it is suggested that an ADFM be used to monitor discharges. Furthermore, if feasible, it is recommended that head losses within the force main be measured under a variety of discharges in order to evaluate pipe roughness under field conditions.

Acknowledgements

The author wishes to express appreciation to Rodrigo Musalem for arranging the field reconnaissance and providing the necessary construction drawings; to Lisa Kreiger of the Okeechobee FS for obtaining the pump performance data and providing useful information regarding the force main properties; to Rich Virgil for sharing his expertise on pump station construction and pipe installation techniques; and to Prof. Steven Barfuss of the Utah State Water Research Laboratory for providing insight into the hydraulic properties of HDPE pipe.

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Introduction

The Nubbin Slough / New Palm STA is one of the Critical Restoration Projects authorized by Congress through Section 528 of the 1996 Water Resources Development Act. The STA is approximately 6.5 miles southeast of the city of Okeechobee, adjacent to Nubbin Slough, immediately north of the State Road 710 and just east of the bridge that spans Nubbin Slough. The southern end of this project is approximately 1.3 miles from the edge of Lake Okeechobee. The STA occupies approximately 809 acres of a 2,135-acre site purchased by the SFWMD. A comprehensive description of the STA, its component configuration and operational plan is provided by Goforth (2005).

Water from Nubbin Slough is diverted into the STA at its western boundary exclusively through pump station S-385. This structure discharges through a force main approximately 1 kilometer long that terminates in a storage pond located in the middle of the STA. Pumping commences when the stage within the pump station wet well rises to 20 feet NGVD. It then ceases when the wet well stage falls to 17 feet NGVD. Regardless of the head water stage at the pump station, pumping will be terminated when the stage within the storage pond rises to an elevation of 37.5 feet NGVD. This results in a maximum static head of 20.5 feet.

The pump station has four submersible, 20-inch diameter centrifugal pumps with 215-horsepower electric-powered motors. Goforth (2005) indicates that each pump has a nominal discharge capacity of approximately 36 cfs pumping against a static head of 19 ft, although friction and other energy losses within the piping system reduce the total pump station capacity. While this operating condition is possible, the actual discharge will vary somewhat with the static head and assumed head loss parameters.

Objectives and Scope

The primary purpose of the rating analyses conducted in this study is to enable flows through S-385 to be estimated using measured head water elevations, tail water elevations and pump engine speeds. A secondary objective is to estimate the range of expected pipeline velocities in order to help ensure that the most appropriate flow measuring equipment is used. The hydraulic rating equations are based on pump performance characteristics, hydraulic properties of the pump station piping and appurtenances, and sound engineering principles. Since S-385 became operational only recently, the rating equations could not be calibrated to stream flow measurements since none were available at the time this rating analysis was conducted.

Station Design

Cross sectional and plan views of the pump station design are shown in figure 1. Figure 2 shows the design profile of the force main that connects the pump station with the central storage pond. Unlike most SFWMD pump stations, all four of the pumps discharge into a common header that is directly connected to the force main. Table 1a contains the dimensions of the station piping while table 1b lists the appurtenances located between each pump and the common header pipe. Listed also are the head loss coefficients. Table 1c contains estimates of pipe roughness.

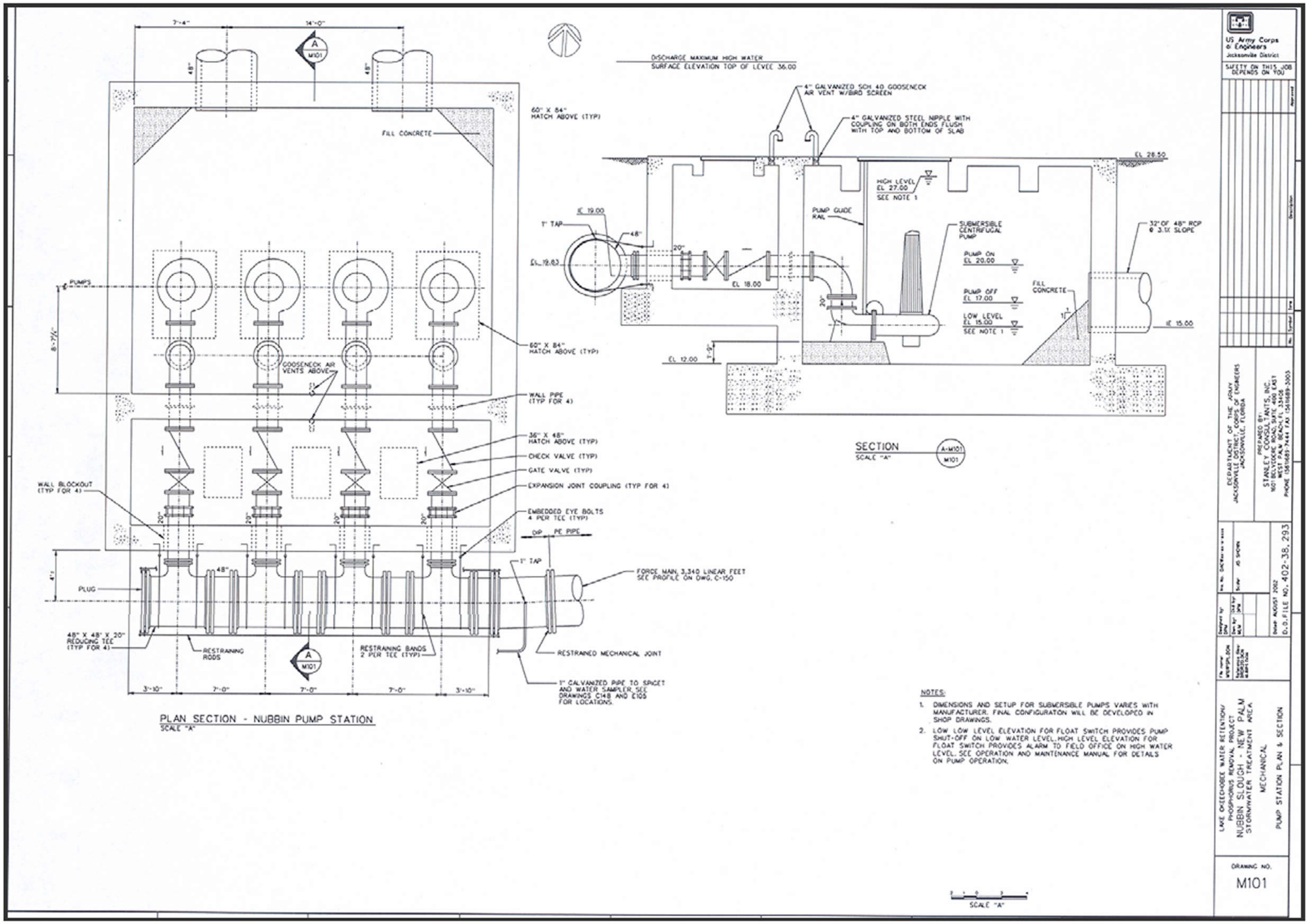

Figure 1. Design of S-385

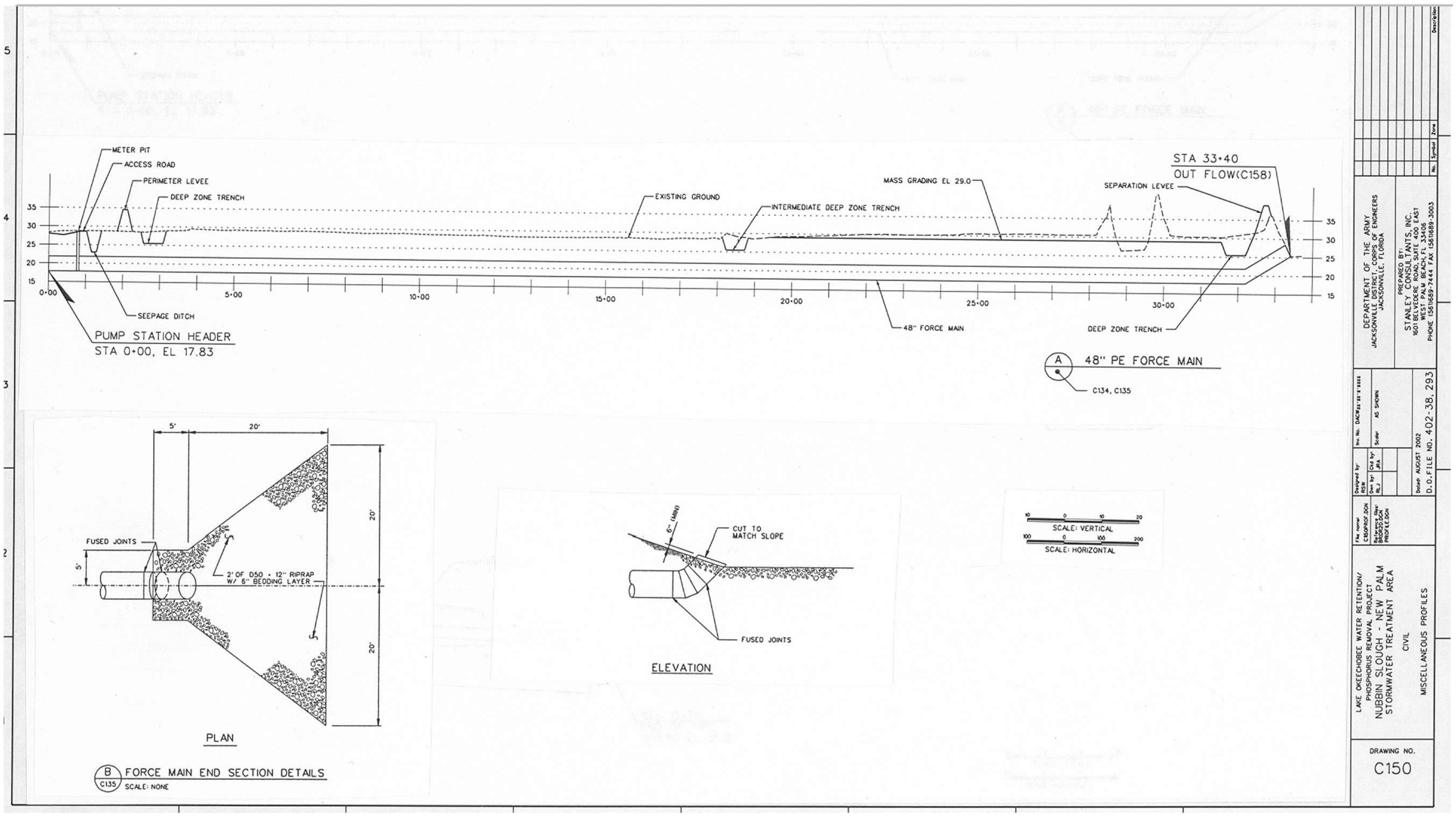

Figure 2. Force Main Design

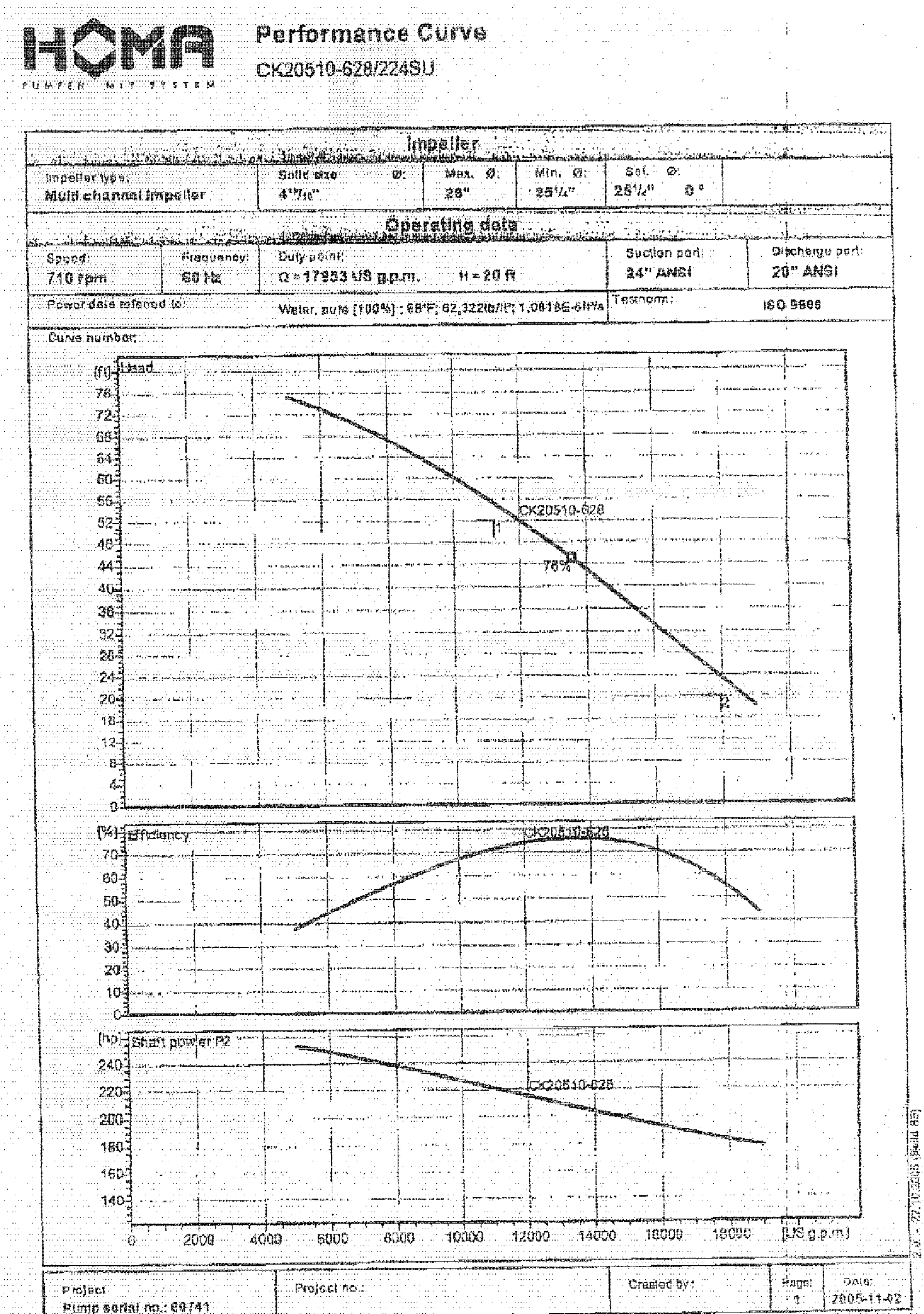

Figure 3. Pump Performance Curves

Table 1a. Dimensions of station piping

Conduit	Dimension	Value	Source
Local Discharge Pipe	OD (in)	21.6	*Sanks(1989); Hyd Inst(1990)*
	Metal Wall Thickness (in)	0.45	*Sanks(1989); Hyd Inst(1990)*
	Mortar Lining Thickness (in)	0.09375	*Sanks(1989); DIPRA Handbk*
	ID (in)	20.5	*Construction Drawings*
	ID(ft)	1.709	
	Length (ft)	23.0	
	Area (sq ft)	2.29	
Header	OD (in)	50.8	*Sanks(1989); Hyd Inst(1990)*
	Metal Wall Thickness (in)	0.72	*Sanks(1989); Hyd Inst(1990)*
	Mortar Lining Thickness (in)	0.125	*Sanks(1989); DIPRA Handbk*
	ID (in)	49.1	*Construction Drawings*
	ID(ft)	4.093	
	Length (ft)	32.0	
	Area (sq ft)	13.15	

Similarly, tables 2 contain the corresponding specifications for the force main. The pump performance curves are shown in figure 3.

At the time this rating analysis was carried out, no as-built drawings were available. Hence, construction Drawings were used Instead. It is therefore possible that corrections and revisions to this analysis may be necessary after the as-built drawings are obtained.

Table 1b. Station appurtenances and local head loss coefficients

Conduit	Number	Appurtenance	Local Loss Coefficient			Sources
			K_{min}	K_{ave}	K_{max}	
Local Discharge Pipe	2	90° flanged, long-radius elbow	0.14	0.18	0.23	*Sanks (1989)*
	1	check valve	0.60	1.40	2.20	*Sanks (1989)*
	1	gate valve	0.02	0.03	0.05	*Hydraulic Institute (1990)*
	1	branch tee	0.26	0.40	0.54	*Hydraulic Institute (1990)*
	sum	$\Sigma K =$	1.16	2.19	3.25	
Header	4	in-line tee	0.05	0.07	0.09	*Hydraulic Institute (1990); Sanks(1989)*
	sum	$\Sigma K =$	0.18	0.28	0.38	

Table 1c. Roughness of station piping

ε (ft)	value	Sources	Comments
Minimum	0.000005	*Hydraulic Institute (1990)*	Moody Diagram Roughness Chart
Expected	0.0002	*computed from C=150(see App B; also DIPRA)*	new, cement lined DIP
Maximum	0.0005	*computed from C=140(see App B; also DIPRA)*	aged, cement lined DIP

Methodology

The procedure implemented here for developing the rating curves reflects the standard procedure presented by Imru and Wang (2004). However, the station piping configuration for S-385

Table 2a. Force main dimensions

Dimension	Value	Source
OD (in)	47.823	
Wall Thickness (in)	1.477	*manufacturer*
ID (in)	44.869	*manufacturer*
ID (ft)	3.739	
Length (ft)	3340.0	*const plans*
Area (sq ft)	10.98	

necessitates a more complicated analysis than is typically required. In particular, all four of the pumps discharge into a common header pipe that is connected to the force main. This essentially constitutes a system where up to four pumps can be operating in parallel. Theoretically speaking, when more than one pump is operating, each pump cannot be rated individually. It still may be possible from a practical viewpoint to rate the pumps individually if the head losses through the force main are small or vary little over the expected range of flows. Unfortunately, given the long length of the force main, this would not be a good assumption. Hence, the pumps at S-385 will be rated either as a single pump in operation or as groups of two, three or four pumps operating in parallel.

Table 2b. Force main appurtenances and local loss coefficients

Number	Appurtenance	Local Loss Coefficients			sources
		K_{min}	K_{ave}	K_{max}	
1	45° flanged, mitered elbow	0.16	0.20	0.26	*Sanks (1989)*
1	submerged exit	1.00	1.00	1.0	

Table 2c. Estimated force main roughness

ε/D	Value	Sources
Minimum	smooth pipe	*See App C; Barfuss (2006)*
Maximum	0.00001	

Since no measured flow data exist at S-385, the approach for rating analysis essentially consists of the following steps:

1. Obtain the manufacturer's performance curve that depicts the relationship between total dynamic head (TDH) and flow rate.
2. Subtract from the performance curve all head losses between the pump and the point where the pump discharge line connects to the common header pipe.
3. For the number of pumps operating in parallel, add the modified performance curves obtained in step 2, assuming all pumps are connected at the beginning of the force main (head losses within the header can be neglected; see appendix A).
4. Subtract the head losses incurred within the force main from the composite performance curve obtained in step 3. This results in the relationship between discharge and total static head (TSH) between the pump station wet well and the storage pond.
5. Fit the case 8 model to each of the modified, composite performance curve determined in step 4.

This procedure will yield a total of four rating equations since one, two, three or four pumps can be operating.

Rating Analysis

The model rating equation applied to S-385 is the standard case 8 model (Imru and Wang, 2004):

$$Q = A\left(\frac{N}{N_O}\right) + BH^C\left(\frac{N_O}{N}\right)^{2C-1} \qquad (1)$$

Where Q is the discharge at N RPM, H is the TSH, N_O is the design engine or pump speed, and A, B and C are coefficients to be 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, $N_O = N$ so the ratios involving these parameters are eliminated.

Figure 4 depicts the TSH vs. flow relationship for one, two, three and four pumps operating in parallel. For comparative purposes, the TDH vs. flow relationship (i.e. the pump performance curve reflecting the number of pumps operating) is also shown for each pumping scenario. The associated head loss computations are provided in appendix D. Equation (1) was fit to each of the TSH vs. Q curves shown in figure 4. The resulting values of A, B and C are provided in table 3. Tables 4 provide a comparison of each rating equation with its respective pump station performance curve. The highlighted rows in each table represent the approximate range of static heads expected in the field.

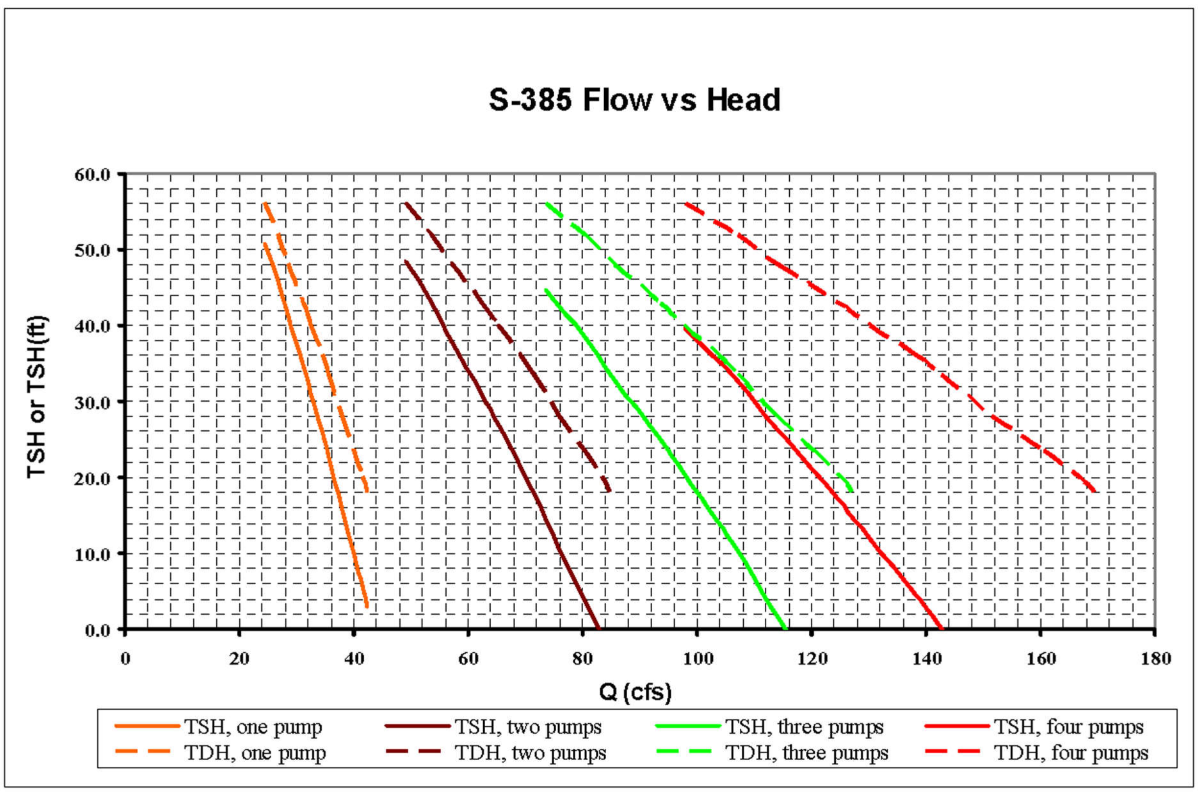

Figure 4. TSH vs. discharge rating curves for S-385

Table 3. Values of A, B and C in equation 1

Regression Parameter	Number of Pumps in Operation			
	1	*2*	*3*	*4*
A	43.060	81.911	114.900	142.600
B	-0.216	-0.399	-0.562	-0.852
C	1.132	1.135	1.130	1.074

Table 4a. Comparison of the regression equation and pump station performance curve for one pump operating

TSH	Q (p.s. perf. curve)	Q (regression)	%Error
50.88	24.51	24.60	0.35
45.93	26.74	26.62	-0.45
41.10	28.52	28.56	0.13
34.76	31.20	31.06	-0.42
31.04	32.53	32.51	-0.07
25.93	34.54	34.45	-0.26
22.79	35.65	35.62	-0.08
15.92	37.88	38.10	0.58
9.99	40.11	40.14	0.06
5.44	41.67	41.59	-0.19
2.98	42.34	42.32	-0.05

Table 4b. Comparison of the regression equation and pump station performance curve for two pumps operating

TSH	Q (p.s. perf. curve)	Q (regression)	%Error
48.47	49.02	49.26	0.47
43.09	53.48	53.33	-0.27
37.92	57.05	57.19	0.26
31.00	62.39	62.24	-0.24
26.99	65.07	65.11	0.06
21.38	69.08	69.01	-0.10
17.95	71.31	71.33	0.04
10.51	75.76	76.15	0.51
3.96	80.22	80.01	-0.27

Discharge and Velocity Ranges

In order to estimate the expected range of operating conditions, system performance curves were computed for the expected minimum and maximum head losses. These losses were based on minimum and maximum static heads of 10 feet and 20.5 feet NGVD, respectively. The curves for a one-pump and four-pump operation are plotted in figures 5 and 6, respectively, along with the estimated range of pump station performance curves. The bounded area in each figure represents the estimated range of operating conditions. If a single pump is operating, it is evident that discharges could range from about 35 cfs to 42 cfs. This corresponds to a velocity range of 3.2 to 3.8 ft/s. Similarly, with all pumps operating, discharges could range from 117 cfs to 136 cfs. In this case velocities would range from 10.7 to 12.4 cfs.

Summary and Conclusions

A rating analysis of S-385 was carried out using the conventional case 8 model. Four rating equations were developed since up to four pumps can be operating in parallel and they discharge into a common force main. All four equations yield discharge rates that are within 0.6% of the discharges derived from the pump station rating curve under the expected range of static heads.

Table 4c. Comparison of the regression equation and pump station performance curve for three pumps operating

TSH	Q (p.s. perf. curve)	Q (regression)	%Error
44.74	73.54	73.69	0.21
38.69	80.22	79.93	-0.36
32.92	85.57	85.77	0.23
25.10	93.59	93.46	-0.14
20.59	97.60	97.76	0.16
14.20	103.62	103.63	0.01
10.37	106.96	107.00	0.04
2.02	113.65	113.65	0.01

Table 4d. Comparison of the regression equation and pump station performance curve for four pumps operating

TSH	Q (p.s. perf. curve)	Q (regression)	%Error
39.67	98.05	98.22	0.18
32.74	106.96	106.49	-0.44
26.23	114.09	114.14	0.04
17.15	124.79	124.57	-0.18
11.99	130.13	130.32	0.15
4.57	138.16	138.25	0.06
0.17	142.61	142.47	-0.10

Additionally, under the expected range of static heads, it was found that discharges can range from about 35 cfs with a single pump operating to about 136 cfs with all pumps operational.

Given the uncertainties inherent to the hydraulic head loss calculations, it is recommended that the rating equations be recalibrated with measured flows. Because of the hydraulic conditions at the downstream end of the force main, it is suggested that an ADFM be used to monitor discharges. Furthermore, if feasible, it is recommended that head losses within the force main be measured under a variety of discharges in order to evaluate pipe roughness under field conditions.

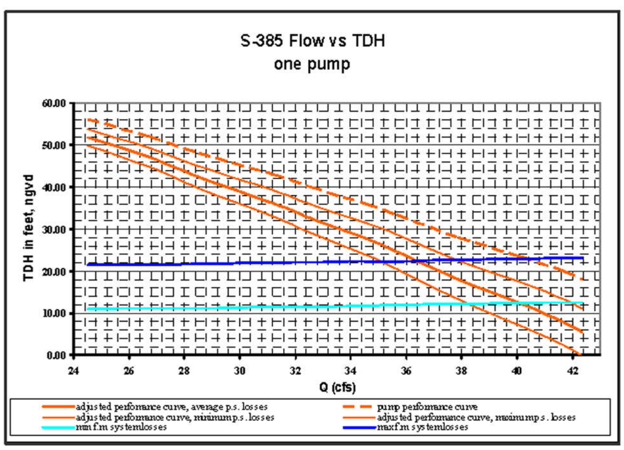

Figure 5. System and pump station performance curves with a single pump operation

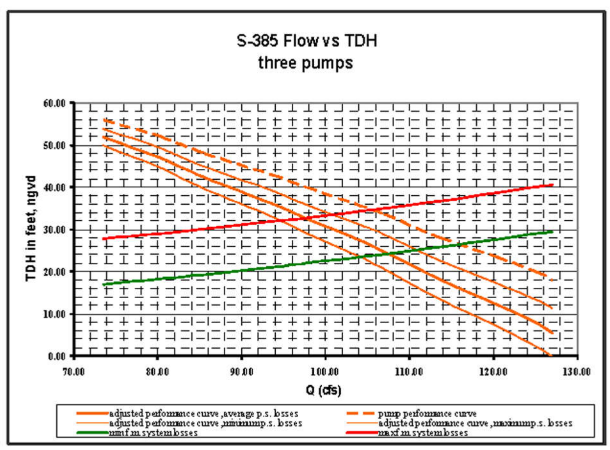

Figure 6. System and pump station performance curves with a three- pump operation

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Appendix A. Evaluation of Head Losses Within the Station Header Pipe

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0630
Rev.11/97

Project: S-385 RATING ANALYSIS — Sheet No. 1 of 1
Subject: HEAD LOSS IN HEADER PIPE — Job No. / Program Code: P
Engineer: WILSNACK — Date: [illegible] Checked By:

FROM PREVIOUS CALCULATIONS, ϵ_{MAX} FOR LINED DIP ≈ 0.0005 FT. FOR 48" ϕ LINED DIP,

$D = 4.093$ FT AND $A = 13.15$ FT^2

@ $Q = 36$ CFS, $V = \frac{Q}{A} = \frac{36}{13.15} = 2.74$ FT/S

ASSUMING $\nu \approx 10^{-5}$ FT^2/S,

$$Re = \frac{DV}{\nu} = \frac{(4.093)(2.74)}{(10^{-5})} = 1.12 \times 10^6$$

$$\frac{\epsilon}{D} = \frac{0.0005}{4.093} = 0.00012$$

$$\rightarrow f \approx 0.0135$$

$$Sf_{MAX} = \frac{f}{D}\frac{V^2}{2g} = \left(\frac{0.0135}{4.093}\right)\frac{(2.74)^2}{(64.4)} = 0.000385$$

FOR A 30 FT LENGTH, $hf_{MAX} = (30)(0.000385) = 0.012$ FT

— CAN IGNORE FRICTION LOSS IN HEADER

FOR A FLOW-THRU T, $K \approx 0.05$ AND $h_m = (0.05)\frac{(2.74)^2}{(64.4)}$

$= 0.0058$ FT $\longrightarrow$ CAN NEGLECT HEAD LOSSES IN THE HEADER ALTOGETHER, CONSIDERING MAGNITUDE OF OTHER LOSSES

Appendix B. Estimated Roughness Range for Lined DIP

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-385 RATING ANALYSIS Sheet No. 1 of 2
Subject: ESTIMATE ROUGHNESS FOR LINED DIP Job No. / Program Code: P
Engineer: WILSNACK Date: 12/13/06 Checked By: ____

FOR CEMENT/MORTAR-LINED DIP, $C = 140$ ACCORDING TO DIPRA. THIS IMPLIES

$$V = 1.32\, C\, R^{0.63}\, S^{0.54}$$

$$V^{1.85} = 1.67\, C^{1.85}\, R^{1.166}\, S$$

$$S = 0.6 \left(\frac{V}{C}\right)^{1.85} R^{-1.166}$$

ALSO,

$$S = \frac{f}{D}\,\frac{V^2}{2g} = \frac{f}{4R}\,\frac{V^2}{2g} = \frac{f}{8Rg}\,V^2$$

SO,

$$0.6 \left(\frac{V}{C}\right)^{1.85} R^{-1.166} = \frac{f}{8Rg}\,V^2$$

$$\boxed{f = \frac{194.6}{C^{1.85}\, V^{0.15}\, D^{0.166}}}$$

20" Ø DIP IS A VALID Q FOR H-W EQ; MUST CHOOSE A VALID V: ASSUME 3 FT/S AND D = 20.5".

$$f_{140} = \frac{194.6}{(140)^{1.85}(3)^{0.15}\left(\frac{20.5}{12}\right)^{0.166}} = 0.0162 \quad \text{FOR } C = 140$$

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0830
Rev.11/07

Project: S-385 RATING ANALYSIS Sheet No. 2 of 2
Subject: ESTIMATE ROUGHNESS OF DIP Job No. / Program Code: P
Engineer: WILSNACK Date: 12/13/06 Checked By:

$$f_{150} = (0.0162)\left(\frac{140}{150}\right)^{1.85} = 0.0143 \quad \text{FOR} \quad C=150$$

$$Re = \frac{DV}{\nu} = \frac{(20.5)(3)}{(12)(10^{-5})} = 5.13 \times 10^{5}$$

$$@ f_{140}, \quad \frac{\epsilon}{D} \approx 0.0003$$

$$@ f_{150} \quad \frac{\epsilon}{D} \approx 0.0001$$

$$0.0001 \leq \frac{\epsilon}{D} \leq 0.0003$$

$$0.00017' \leq \epsilon \leq 0.00051'$$

$$\text{USE} \quad \epsilon_{MAX} = 0.0005 \text{ FT}$$

$$\epsilon_{EXPECTED} = 0.0002 \text{ FT} \quad \text{FOR NEW PIPE}$$

$$\epsilon_{MIN} = 0.000005 \text{ FT} \quad \text{FOR SMOOTH PIPE}$$

Appendix C. Estimated Roughness Range for HDPE Pipe

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-385 RATING ANALYSIS Sheet No. 1 of 2
Subject: ESTIMATED ROUGHNESS FOR HDPE PIPE Job No. / Program Code: P
Engineer: WILSNACK Date: 12/19/06 Checked By:

FOR THE HDPE FORCE MAIN, $D_i = 3.739'$ $A_i = 10.98\ ft^2$

$\epsilon = 0.000005$ FT (PVC PIPE HANDBOOK)

$$S = \frac{f}{2Dg} V^2 \quad (D\ W)$$

$$V^2 = \frac{2.22}{n^2}\left(\frac{D}{4}\right)^{4/3} S$$

$$S = \frac{2.86\ n^2}{D^{4/3}} V^2 \quad (\text{MANNING})$$

$$\frac{2.86\ n^2}{D^{4/3}} V^2 = \frac{f}{2Dg} V^2$$

$$\boxed{f = \frac{5.72\ g\ n^2}{D^{1/3}}}$$

FOR $n = 0.009$ (MANUFACTURER LITERATURE),

$$f = \frac{(5.72)(32.2)(0.009)^2}{(3.739)^{1/3}} = 0.00961$$

@ 36 CFS, $V = 3.28$ FT/S

@ 36×4 CFS, $V = 13.11$ FT/S

South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev. 11/97

Project: S-385 RATING ANALYSIS Sheet No. 2 of 2
Subject: ESTIMATE ROUGHNESS FOR HDPE PIPE Job No. / Program Code: P
Engineer: WILSNACK Date: 12/13/06 Checked By:

@ V = 3 ft/s, $Re = (3.735)(3)(10^5) = 1.12 \times 10^6$

FROM MOODY DIAGRAM, $\frac{\epsilon}{D} < 10^{-6}$; CAN'T DETERMINE ϵ.

@ V = 13 ft/s, $Re = \left(\frac{13}{3}\right)(1.12)(10^6) = 4.9 \times 10^6$

FOR $f = 0.00961$, $\frac{\epsilon}{D} \approx 0.00001 \Rightarrow \epsilon \approx 0.000027$ ft

- ESTIMATE VELOCITY THAT n = 0.009 MAY HAVE BEEN DERIVED FROM. ASSUME $S \approx 0.001$ AND $D \approx 3$.

$$V = \left(\frac{1.49}{0.009}\right)\left(\frac{3}{4}\right)^{2/3}\sqrt{0.001} = 4.32 \text{ ft/s}$$

ASSUME $V \approx 4$ ft/s. THEN, $Re = \left(\frac{4}{3}\right)(1.12)(10^6)$
$= 1.5 \times 10^6$

FOR $f = 0.00961$ AND $Re = 1.5 \times 10^6$, $\frac{\epsilon}{D} < 10^{-6}$

∴ ALL THIS SUGGESTS ϵ CORRESPONDS TO SMOOTH PIPE AS DOES PVC.

USE → $\boxed{\left(\text{SMOOTH PIPE } \frac{\epsilon}{D}\right) \leq \frac{\epsilon}{D} \leq 0.00001}$

Appendix D. Head Loss Calculations

Table D1. Head loss calculations for the station piping

710 RPM						f			hl = f(L/D)V2/2g			$h_m = \Sigma KV^2/2g$			Total Station Head Loss		
TDH(ft)	Q (GPM)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	min	expected	max	min	expected	max	min	expected	max	min	expected	max
56.00	11000.0	24.51	10.68	1825768	1.77	0.0105	0.0132	0.0154	0.25	0.32	0.37	2.06	3.88	5.76	2.31	4.19	6.13
52.00	12000.0	26.74	11.65	1991747	2.11	0.0103	0.0132	0.0153	0.29	0.37	0.43	2.45	4.62	6.86	2.74	4.99	7.29
48.00	12800.0	28.52	12.43	2124530	2.40	0.0102	0.0131	0.0153	0.33	0.42	0.49	2.79	5.25	7.80	3.12	5.68	8.30
43.00	14000.0	31.20	13.59	2323705	2.87	0.0101	0.0131	0.0153	0.39	0.50	0.59	3.34	6.28	9.33	3.73	6.79	9.92
40.00	14600.0	32.53	14.18	2423292	3.12	0.0100	0.0130	0.0153	0.42	0.55	0.64	3.63	6.83	10.15	4.05	7.38	10.79
36.00	15500.0	34.54	15.05	2572673	3.52	0.0099	0.0130	0.0152	0.47	0.62	0.72	4.09	7.70	11.44	4.56	8.32	12.16
33.50	16000.0	35.65	15.54	2655663	3.75	0.0098	0.0130	0.0152	0.49	0.66	0.77	4.36	8.21	12.19	4.85	8.86	12.96
28.00	17000.0	37.88	16.51	2821642	4.23	0.0098	0.0130	0.0152	0.56	0.74	0.87	4.92	9.27	13.76	5.48	10.00	14.63
23.50	18000.0	40.11	17.48	2987621	4.74	0.0097	0.0129	0.0152	0.62	0.83	0.97	5.52	10.39	15.43	6.14	11.21	16.40
20.00	18700.0	41.67	18.16	3103806	5.12	0.0096	0.0129	0.0152	0.66	0.89	1.05	5.95	11.21	16.65	6.62	12.10	17.70
18.00	19000.0	42.34	18.45	3153599	5.29	0.0096	0.0129	0.0152	0.68	0.92	1.08	6.15	11.57	17.19	6.83	12.49	18.27

Table D2. Expected force main head losses with one pump operating

TDH(ft)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$hl = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total FM Head Loss
51.81	24.51	2.23	834676	0.08	0.0120	0.83	0.09	0.92
47.01	26.74	2.44	910555	0.09	0.0118	0.97	0.11	1.08
42.32	28.52	2.60	971259	0.10	0.0117	1.10	0.13	1.22
36.21	31.20	2.84	1062315	0.13	0.0116	1.30	0.15	1.45
32.62	32.53	2.96	1107842	0.14	0.0116	1.42	0.16	1.58
27.68	34.54	3.15	1176134	0.15	0.0114	1.56	0.18	1.75
24.64	35.65	3.25	1214074	0.16	0.0113	1.65	0.20	1.85
18.00	37.88	3.45	1289953	0.18	0.0112	1.85	0.22	2.07
12.29	40.11	3.65	1365833	0.21	0.0111	2.05	0.25	2.29
7.90	41.67	3.79	1418949	0.22	0.0110	2.19	0.27	2.46
5.51	42.34	3.86	1441713	0.23	0.0109	2.25	0.28	2.53

Table D3. Expected force main head losses with two pumps operating

TDH(ft)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$hl = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total FM Head Loss
51.81	49.02	4.46	1669352	0.31	0.0107	2.97	0.37	3.34
47.01	53.48	4.87	1821111	0.37	0.0106	3.47	0.44	3.92
42.32	57.05	5.20	1942518	0.42	0.0104	3.90	0.50	4.40
36.21	62.39	5.68	2124629	0.50	0.0103	4.61	0.60	5.21
32.62	65.07	5.93	2215685	0.55	0.0102	4.97	0.65	5.62
27.68	69.08	6.29	2352268	0.61	0.0101	5.56	0.74	6.30
24.64	71.31	6.49	2428148	0.65	0.0101	5.90	0.79	6.68
18.00	75.76	6.90	2579907	0.74	0.0100	6.60	0.89	7.48
12.29	80.22	7.31	2731666	0.83	0.0099	7.33	0.99	8.32
7.90	83.34	7.59	2837898	0.89	0.0099	7.89	1.07	8.96

Table D4. Expected force main head losses with three pumps operating

TDH(ft)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$hl = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total FM Head Loss
51.81	73.54	6.70	2504027	0.70	0.0100	6.23	0.84	7.06
47.01	80.22	7.31	2731666	0.83	0.0099	7.33	0.99	8.32
42.32	85.57	7.79	2913777	0.94	0.0098	8.28	1.13	9.41
36.21	93.59	8.52	3186944	1.13	0.0097	9.76	1.35	11.12
32.62	97.60	8.89	3323527	1.23	0.0096	10.56	1.47	12.03
27.68	103.62	9.44	3528402	1.38	0.0096	11.82	1.66	13.48
24.64	106.96	9.74	3642222	1.47	0.0095	12.50	1.77	14.27
18.00	113.65	10.35	3869860	1.66	0.0094	13.98	2.00	15.97
12.29	120.33	10.96	4097499	1.86	0.0093	15.57	2.24	17.80

Table D5. Expected force main head losses with four pumps operating

TDH(ft)	Q(cfs)	V(ft/s)	N_R	$V^2/2g$ (ft)	f	$hl = f(L/D)V^2/2g$	$h_m = \Sigma KV^2/2g$	Total FM Head Loss
51.81	98.05	8.93	3338703	1.24	0.0096	10.65	1.49	12.14
47.01	106.96	9.74	3642222	1.47	0.0095	12.50	1.77	14.27
42.32	114.09	10.39	3885036	1.68	0.0094	14.08	2.01	16.09
36.21	124.79	11.36	4249259	2.01	0.0093	16.65	2.41	19.06
32.62	130.13	11.85	4431370	2.18	0.0092	18.01	2.62	20.63
27.68	138.16	12.58	4704536	2.46	0.0092	20.16	2.95	23.11
24.64	142.61	12.99	4856295	2.62	0.0091	21.32	3.14	24.47
18.00	151.53	13.80	5159814	2.96	0.0091	23.96	3.55	27.51