Flow Rating Analysis for Pump Station S-331

Technical Publication ERA # 456

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Executive Summary

An improved rating equation based on the case 8 model was developed for S-331 using measured flow data that were acquired when static heads across the pump station were greater than zero. Comparisons were made between this rating and the existing rating equation that is based on the case 3 model. At a given static head and engine speed, the existing rating equation produces discharge rates that are significantly higher than the measured values. It was determined that flows computed with the existing rating equation deviate from measured flows by approximately 4 – 18 % at an engine speed of 1400 RPM. In contrast, discharges at this speed computed with the new equation differ from the corresponding measured values by about 2 – 11%. However, only one of the computed values deviates from the associated measured value by more than 2%. This measured flow rate is of a lower quality than the other two flows measured at this speed and is probably less indicative of the rating equation performance. At 1800 RPM, deviations from measured flows range from about 11 – 18% for the discharges computed with the existing equation while all of the flows computed with the proposed equation are within 6% of the corresponding measured values. Given these results along with the fact that the existing rating cannot be substantiated, it is recommended that the new rating replace the current one.

Since flows through S-331 are often siphoned, a new rating curve for siphoned flows was also developed since no background information on the existing rating could be located. It was found that siphoned flows based on the existing rating were generally within the uncertainty limits of the corresponding flows determined with the new rating. Consequently, no revisions to the existing rating are recommended at this time.

An impact analysis of the revised rating for pumped flows was carried out over a ten-year period of record starting on June 1, 1997 and ending May 31, 2007. Using the historical break-point data, mean daily pumped flows were computed with both equations and compared. The new rating equation produced mean daily flows that averaged about 12% lower than those computed by the existing rating equation. A reload of computed flows into DBHYDRO is recommended.

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Introduction

S331 is a three-unit pump station located in L-31N borrow canal near Homestead, Florida. According to Iteration 7 of the experimental program of water deliveries to ENP, this structure serves the purpose of controlling the stages in L-31N north of S-331 as a function of the water levels in the Rocky Glades residential area. It contains three Allis-Chalmers vertical flow pumps driven by diesel engines rated at 1800 RPM. This pump station is somewhat unique in that it frequently operates in both pumping and siphoning modes. Furthermore, pumping occurs under both positive and negative static heads.

Objectives and Scope

The primary purpose of this study was to upgrade the rating equation for S-331 pumped discharges from a case 3 model to an improved case 8 equation. This effort differs from the one completed previously by Wang and Imru (2006) in that the measured flow data set was further scrutinized and refined based on suggestions provided by stream gauging staff. Also taken into account were the uncertainties inherent to the measured flows. Additionally, the existing rating equation for forward siphoning was also evaluated and compared to available data.

Station Design

Each of the identical diesel engine-driven pumps has an impeller diameter of 96 inches and a design speed of approximately 100 RPM. A cross section of a pump along with its discharge conduit and intake structure is shown in figure 1a while figures 1b and 1c provide the associated elevation and plan views, respectively. Each pump discharges directly into a concrete tunnel whose dimensions are indicated in figure 2. Each tunnel has a submerged outlet. Additional details are provided in USACOE (1978).

Rating Analysis : Siphoning Operations

The existing rating equation for siphoning operations is shown in figure 3 and is expressed as:

$$Q = 130\,(TSH)^{0.41} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where Q is the flow rate and TSH is the total static head across the pump station. No analysis or calculations substantiating this rating could be located. Hence, the relationship between siphoned flow and TSH was recomputed as part of this effort in order to evaluate the current rating. The associated head loss calculations are provided in appendix A while table 1 contains the relevant data and parameters used in the computations. In particular, data and methods provided by Miller (1990) were employed throughout.

Figure 4 shows the siphon rating curve developed in this effort along with the existing rating and the measured flow data given in table 2. Shown also is the estimated uncertainty of the new rating. Although the two rating curves are different, the existing rating falls within the estimated uncertainty limits of the new rating. Furthermore, the limited flow data do not substantiate either

Figure 1a. Cross section of S-331 pumps, intake bays and discharge conduits

Figure 1b. Elevation view of S-331, upstream side

Figure 1c. Plan view of S-331

Figure 2. Discharge conduit dimensions

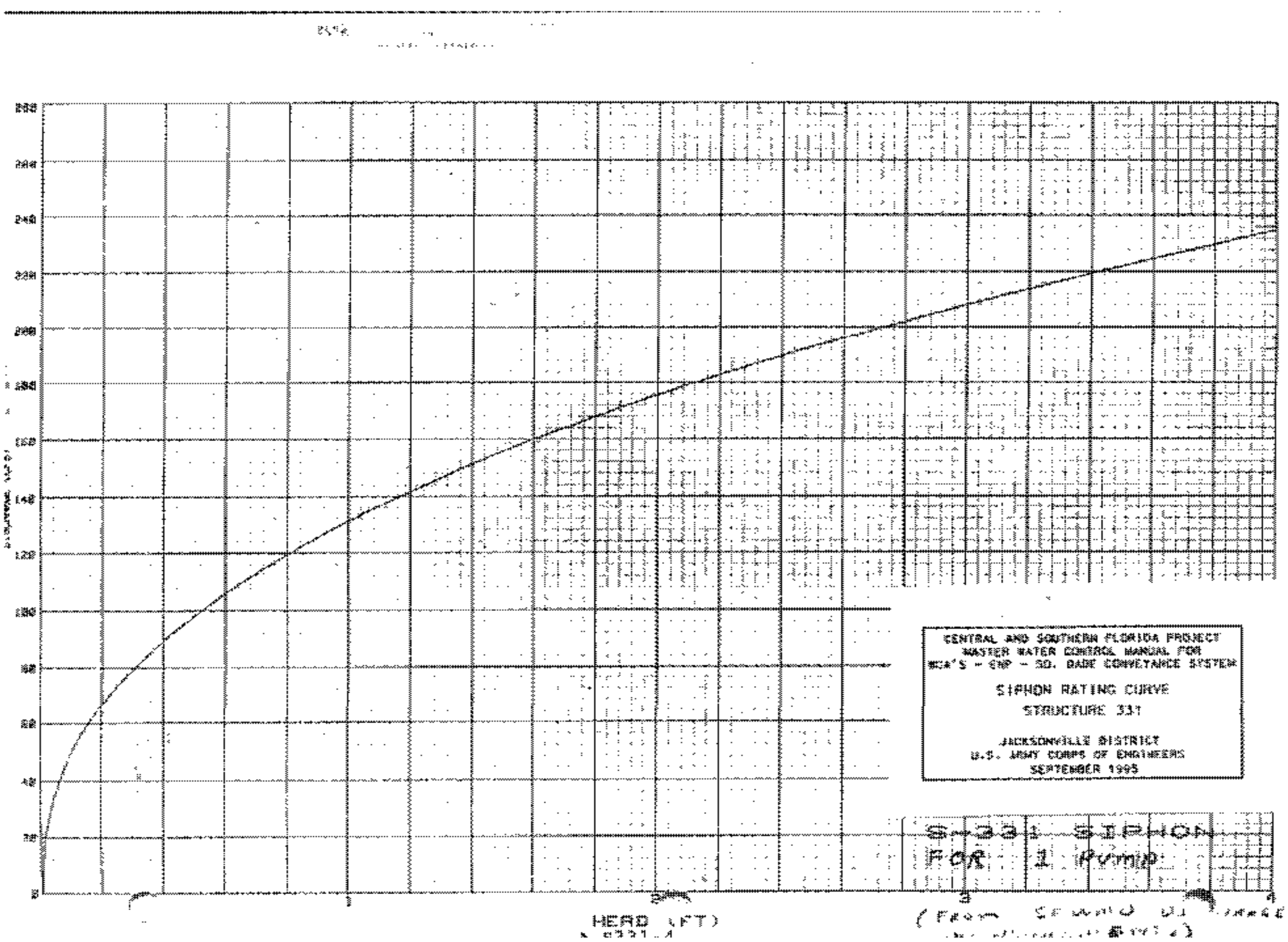

Figure 3. Discharge vs static head for S-311 siphoning

Table 1. Data and parameters used in head loss calculations

Pump Bay			Intake Chamber			Pump			Discharge Elbow			Tunnel		
parameter	*value*	*source*	*parameter*	*value*	*source*	*parameter*	*value*	*source*	*parameter*	*value*	*source*	*parameter*	*value*	*source*
K_{ent}	0.02	Miller(1990)	K_{ent}	0.18	Miller(1990)	K_{ent}	0.80	Daugherty & Franzini(1977)	Φ(ent)	9.13	const-dwgs	K_{cont} @ ent	0	Miller(1990)
bot elev	-11.00	const-dwgs	bot elev	-11.00	const-dwgs	bell ent Φ	12.00	const-dwgs	width (ext)	16.80	const-dwgs	width (ent)	7.15	const-dwgs
width	28.60	const-dwgs	top elev	2.00	const-dwgs	pump Φ	8.00	const-dwgs	hgth (ext)	5.50	const-dwgs	hgth (ent)	5.5	const-dwgs
approx HW	5.00	dbhydro	width	22.80	const-dwgs	K_{cont} (bell)	0.40	Miller(1990)	K_d	0.53	Miller(1990)	ε_{min} (ft)	0.001	Hyd Inst(1990)
						% area open	34.00	(calibrated)	K_b^*	0.28	Miller(1990)	ε_{max} (ft)	0.01	Hyd Inst(1990)
						d/D	0.58		C_o	0.85	Miller(1990)	K_d^*	0.48	Miller(1990)
						C_c	0.76	Miller(1990)				width (ext)	8.75	const-dwgs
						K_o	8.24	Miller(1990)				hgth (ext)	7.00	const-dwgs
												length	27	const-dwgs

rating more than the other. Consequently, the existing rating should remain in use for the time being.

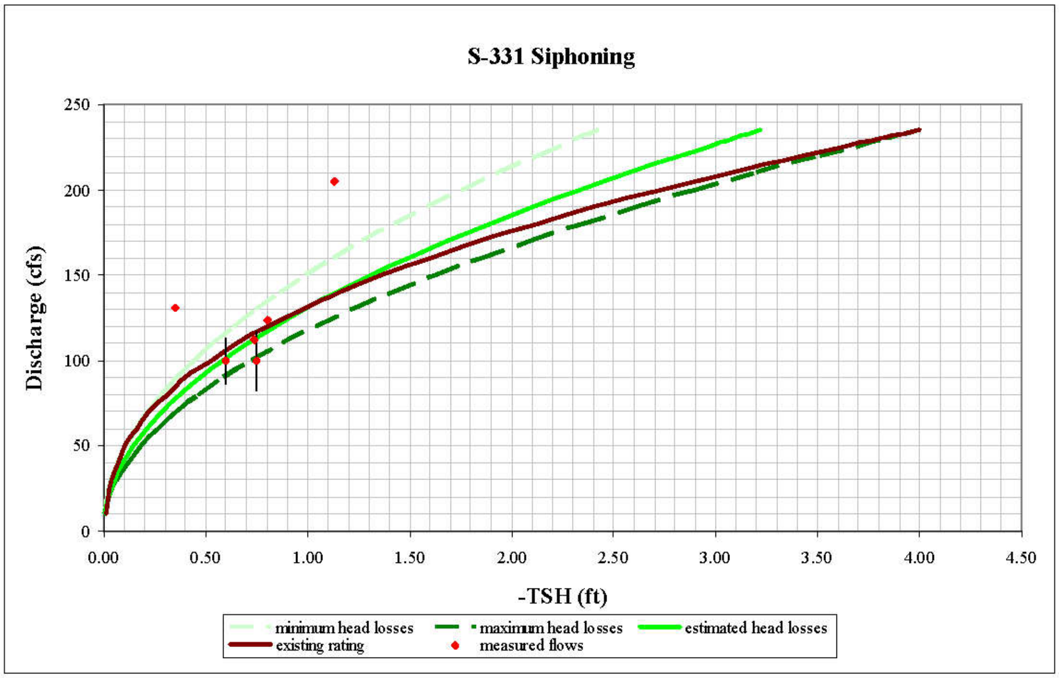

Figure 4. Existing and new rating curves for S-331 siphoning

Table 2. Discharges measured during siphoning

Measurement Date	(-)TSH (ft)	Q (cfs)	* Estimated uncertainty (±cfs)	Quality Tag
25-Apr-97	0.75	99.58	16.86	G
12-Jun-98	0.60	99.57	13.49	
09-Feb-83	0.80	124.00	insufficient data	E
14-Dec-83	0.35	131.00	insufficient data	E
18-Jan-84	0.74	112.00	insufficient data	E
01-Feb-84	1.13	204.67	insufficient data	E

* estimated uncertainty = 95% C.I. + 2% systematic error

Rating Analysis: Pumping Operations

Existing rating

The existing rating equation is based on the case 3 model (Otero, 1995) and expressed as

$$Q = Q_{lwr} + \left(Q_{upr} - Q_{lwr}\right)\left(\frac{N - N_{lwr}}{N_{upr} - N_{lwr}}\right) \tag{2}$$

where Q is associated with engine speed N while Q_{lwr} and Q_{upr} are the discharges at engine speeds N_{lwr} and N_{upr}, respectively. Q_{lwr} and Q_{upr} are computed from

$$Q_{lwr} = C_{10} + C_{11}.H_{lwr} + C_{12}.H_{lwr}^{2} + C_{13}.H_{lwr}^{3} \tag{3a}$$

$$Q_{upr} = C_{20} + C_{21}.H_{upr} + C_{22}.H_{upr}^{2} + C_{23}.H_{upr}^{3} \tag{3b}$$

In equations 3, C_{10} through C_{23} are regression coefficients while H_{lwr} and H_{upr} are the static heads corresponding to Q_{lwr} and Q_{upr}, respectively. H_{lwr} and H_{upr} are obtained from pump affinity laws (Otero 1995) as follows:

$$H_{lwr} = H\left(\frac{N_{lwr}}{N}\right)^{2} \tag{4a}$$

$$H_{upr} = H\left(\frac{N_{upr}}{N}\right)^{2} \tag{4b}$$

In equations 4, H is the static head associated with engine speed N. The regression coefficients for each pump are given in Table 3.

Table 3. Flow coefficients for pumps at S331 in the existing Case 3 rating equation

Unit #	C_{10}	C_{11}	C_{12}	C_{13}	C_{20}	C_{21}	C_{22}	C_{23}	N_{lwr}	N_{upr}
1	370.37	2.87	-20.013	0.78	487.16	-17.47	-1.74	-0.56	1400	1800
2	370.37	2.87	-20.013	0.78	487.16	-17.47	-1.74	-0.56	1400	1800
3	370.37	2.87	-20.013	0.78	487.16	-17.47	-1.74	-0.56	1400	1800

New rating

The development of a hydraulic rating equation for pumping operations should, whenever possible, be based on both the manufacturer's pump performance curve and measured flows. When this information is available, head loss parameters would typically be adjusted so as to calibrate the pump station performance curve (i.e. the discharge versus static head relationship) to the measured data. Unfortunately, the manufacturer's pump performance data could not be obtained. Hence, a revised rating based on stream flow measurements alone was developed.

Table 4 lists the measured flow data that were determined to be adequate for the purposes of this rating analysis. The SAS nonlinear regression procedure NLIN was used to fit the case 8 rating model to these data. The basis of this model is given by Imru and Wang (2003) and expressed as

$$Q = A\left[\frac{N}{N_0}\right] + BH^{C}\left[\frac{N_0}{N}\right]^{2C-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Where Q = the discharge (cfs), N = the measured engine speed (rpm), N_0= the design engine speed (rpm) and H = the measured static head (ft). A, B and C are coefficients to be determined through regression. The resultant values of these coefficients are A = 440, B = -25 and C = 1.5. As indicated previously, N_o = 1800 RPM.

Table 4. Measured flows during pumping

Measurement Date	# pumps operating	Pump Engine Speed (RPM)	TSH (ft)	Unit Q (cfs)	* Estimated uncertainty (±cfs)	Quality Tag
06-Feb-01	1	1400	-0.41	367.51	10.18	E
06-Aug-04	1	1400	0.92	342.25	28.64	F
06-Sep-04	1	1400	0.22	344.25	19.71	G
4-Jun-97	1	1400	0.92	301.63	14.48	E
4-Jun-97	1	1600	1.03	361.26	30.74	F
06-May-98	2	1725	0.15	413.39	34.93	F
06-May-98	2	1800	0.32	435.44	19.72	G
14-Oct-98	1	1800	0.72	407.80	30.58	G
27-Oct-98	1	1800	0.73	400.48	44.29	F
22-Apr-98	2	1800	0.27	434.67	25.23	E
4-Jun-97	1	1800	1.15	395.98	31.05	G

* estimated uncertainty = 95% C.I. + 2% systematic error

Comparisons of the existing and proposed rating equations

Figure 5 displays the pump station rating curves given by each of the models along with the measured flows. Not included in this figure, however, is the measured discharge reflecting the negative static head since $H \geq 0$ in equation 5. At a given static head and engine speed, it is evident that the existing rating equation produces discharge rates that are noticeably higher than the measured values. A comparison between each of the ratings and the measured data is provided in table 5. Flows computed with the existing rating equation deviate from measured flows by approximately 4 – 18 % at the lower engine speed and about 11 – 18% at the upper engine speed. In contrast, discharges at 1400 RPM computed with the new equation differ from the corresponding measured values by about 2 – 11%. However, only one computed value at this engine speed deviates from the associated measured value by more than 2%. This measured flow rate was assigned a quality tag of "Fair". The other two measured flows at this speed were

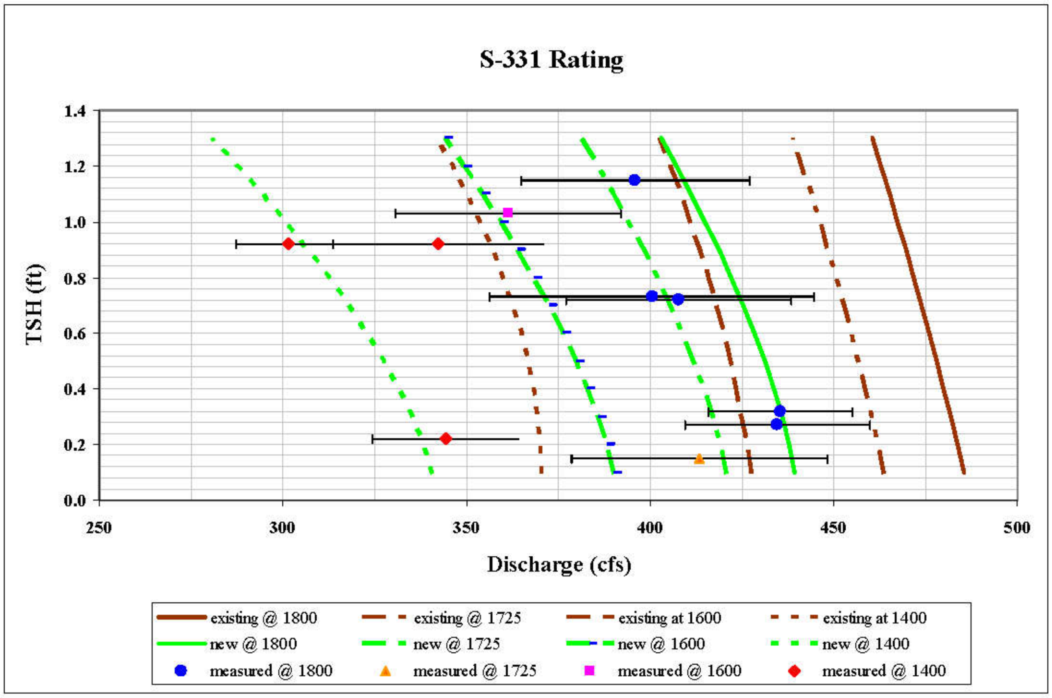

Figure 5. A comparison of the new and existing rating equations with measured flows

Table 5. A comparison of the new and existing rating equations

TSH	RPM	Measured Flows				Existing Rating		New Rating		% Difference in Computed Flow
		Quality Tag	*lower limit*	*estimated*	*upper limit*	flow	% error	flow	% error	
0.22	1400	G	324.54	344.25	363.96	370.04	7.49	337.96	-1.83	-8.67
0.92	1400	F	313.61	342.25	370.89	356.67	4.21	305.75	-10.66	-14.28
0.92	1400	E	287.14	301.63	316.11	356.67	18.25	305.75	1.37	-14.28
1.03	1600	F	330.52	361.26	392.00	410.38	13.60	358.04	-0.89	-12.75
0.15	1725	F	378.46	413.39	448.32	462.92	11.98	420.09	1.62	-9.25
0.27	1800	E	409.43	434.67	459.90	482.30	10.96	436.49	0.42	-9.50
0.32	1800	G	415.72	435.44	455.17	481.37	10.55	435.47	0.01	-9.53
0.72	1800	G	377.22	407.80	438.38	473.47	16.10	424.73	4.15	-10.29
0.73	1800	F	356.19	400.48	444.76	473.26	18.17	424.41	5.98	-10.32
1.15	1800	G	364.93	395.98	427.03	463.91	17.16	409.17	3.33	-11.80

judged to be “Good” and “Excellent”. Hence, they are probably more indicative of the rating equation performance at this speed. At the upper speed of 1800 RPM, deviations from measured flows range from about 11 – 18% for the case 3 computed discharges while all of the flows computed with the proposed case 8 equation are within 6% of the corresponding measured values. Given these results along with the fact that the existing rating cannot be substantiated, it is recommended that the new rating replace the current one.

Computing flows when TSH < 0

As mentioned previously, the case 8 rating model given by equation 5 can only be directly applied to situations where the static head across the pump station is nonnegative; that is, the tail water elevation is not less than the head water elevation. Unfortunately, pumping at S-331 is sometimes initiated when its head water elevation is higher than its tail water elevation. Imru and Wang (2004) encountered similar circumstances at S-13. Their suggestions for rectifying equation 5 to pumping against a negative static head are to (i) use the absolute value of H while reversing the sign of B, or (ii) set H = 0. The former approach seems more physically justified and was tested by comparing computed flows against measured flows under both negative and positive static heads. The results are shown in figure 6. Although the quantity of data is very

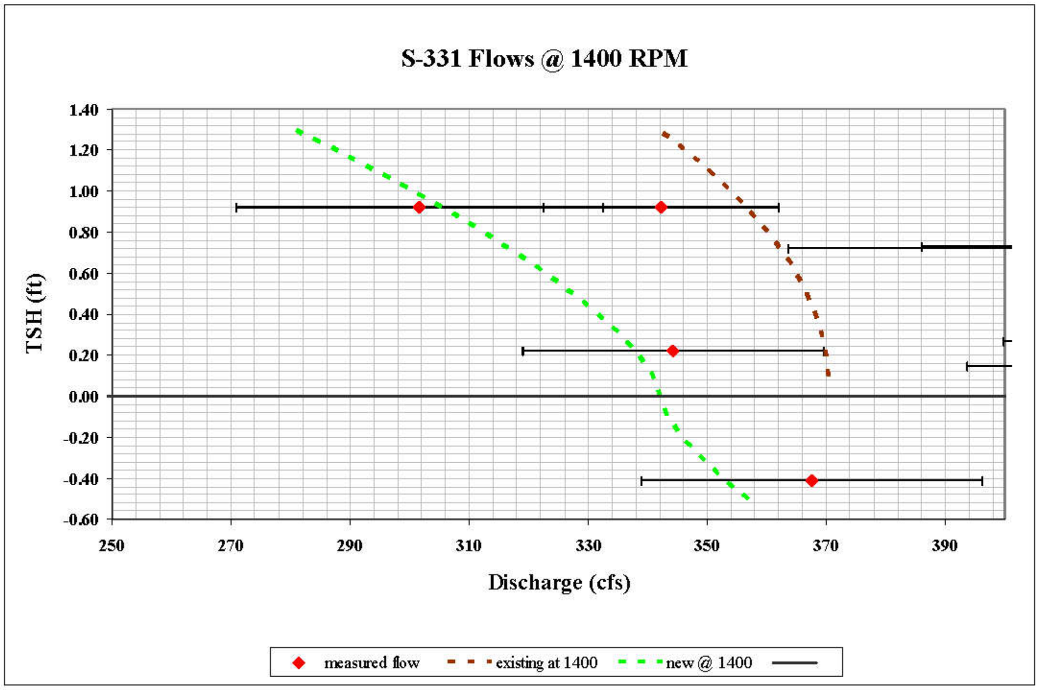

Figure 6. New rating equation at both negative and positive TSH

limited, it appears that the suggested approach for dealing with negative static heads leads to realistic results. Its inclusion into the FLOW program is suggested, although further examination of this approach is recommended.

Impact Analysis

An impact analysis of the revised rating was carried out over a ten-year period of record starting on June 1, 1997 and ending May 31, 2007. Using the historical break-point data, mean daily flows were computed with both equations. Considering only the days when pumping occurred, the new rating equation produced mean daily flows that averaged about 12% lower than those computed by the existing rating equation. The maximum absolute difference was approximately 93%. If days with zero pumping are included, the absolute average difference decreases to about 7%.

Given the changes in mean daily flow values that will result from implementing the new rating, a reload of computed flows into DBHYDRO is recommended. However, this recommendation is ultimately based on the measured stream flow data used in the rating analysis. These data are dated June, 1997 and later. Prior to 1997, it is not clear as to how far back into the period of record these data will accurately reflect pump station performance. Consequently, the period of record that should be subject to data reload cannot be readily identified. Since S-331 only dates back to the early 1980's and the existing rating cannot be substantiated, it is nonetheless recommended that flows over the entire period of record for S-331 be recomputed and reloaded.

Stream Gauging Needs

Siphoning

Currently, only the siphoned flow measurement dated April 25, 1997 (table 2) resides in the QMEAS database and is substantiated by field notes. This measurement falls within a TSH range of -0.5 to -1.0 foot. Table 6 lists the desired siphoned flow measurements for various ranges of TSH. Five measurements are desired within each increment of static head.

Table 6. Stream gauging needs for siphoned flows

(-) TSH Range (ft)	# Measurements
0 – 0.5	5
0.5 – 1.0	4
1.0 – 2.0	5
2.0 – 3.0	5

Pumping

Table 7 lists the desired flow measurements under pumping operations. Five measurements are desired within each increment of static head and engine speed.

Table 7. Stream gauging needs for pumped flows

TSH (ft)	Engine Speed (100 RPM)			
	14 - 15	15 - 16	16 - 17	17 - 18
-(1.0 – 0.5)	5	5	5	5
-(0.5 – 0.0)	4	5	5	5
0.0 – 0.5	4	5	5	2
0.5 – 1.0	4	5	5	3
1.0 – 2.0	5	5	4	4
2.0 – 3.0	5	5	5	5

Summary and Conclusions

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An improved rating equation based on the case 8 model was developed for S-331 using measured flow data that were acquired when static heads across the pump station were greater than zero. The new rating is based on measured flow data alone since the pump performance characteristics are not available. Comparisons were made between this rating and the existing rating equation that is based on the case 3 model. At a given static head and engine speed, the existing rating equation produces discharge rates that are significantly higher than the measured values. It was determined that flows computed with the existing rating equation deviate from measured flows by approximately 4 – 18 % at an engine speed of 1400 RPM. In contrast, discharges at this speed computed with the new equation differ from the corresponding measured values by about 2 – 11%. However, only one of the computed values deviates from the associated measured value by more than 2%. This measured flow rate is of a lower quality than the other two flows measured at this speed and is probably less indicative of the rating equation performance. At 1800 RPM, deviations from measured flows range from about 11 – 18% for the discharges computed with the existing equation while all of the flows computed with the proposed equation are within 6% of the corresponding measured values. Given these results along with the fact that the existing rating cannot be substantiated, it is recommended that the new rating replace the current one.

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References

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Daugherty, R. L. and Franzini, J. B. 1977. *Fluid Mechanics with Engineering Applications, 7th Ed.* McGraw-Hill, New York.

Hydraulic Institute. 1990. *Engineering Data Book, Second Edition*. Hydraulic Institute, Cleveland, Ohio.

Imru, M. and Y. Wang. 2003. Flow Rating Analysis Procedures for Pumps. Technical Publication EMA # 413, South Florida Water Management District, West Palm Beach, Florida, 34 pp.

Imru, M. and Y. Wang. 2004. Flow Rating Analysis Procedures for Pump Station S13. Technical Publication EMA # 416, South Florida Water Management District, West Palm Beach, Florida, 23 pp.

Miller, D. S. 1990. *Internal Flow Systems.* Gulf Publishing Company, Houston, TX.

Otero, J. M. 1995. Computation of Flow Through Water Control Structures. Technical Publication No. 95-03. Hydrology and Hydraulics Division, South Florida Water Management District, West Palm Beach, Florida, 83 pp.

Sanks, R. L. 1989. *Pumping Station Design*. Butterworth Publishers, Stoneham, MA.

USACOE. 1978. Plans for the Construction of Pumping Station 331 and Canal 103 Enlargement.

Wang, Y. and M. Imru. 2006. Rating Analyses for Pump Stations S140, S331, S6, S7, S8. Technical Publication EMA # 436, South Florida Water Management District, West Palm Beach, Florida, 33 pp.

Appendix A. Head Loss Calculations

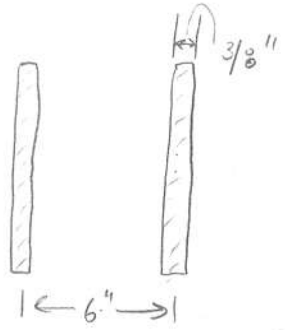
South Florida Water Management District
OPERATIONS & HYDRO DATA MANAGEMENT DIVISION

Calculations

Form #0230
Rev.11/97

Project: S-331 SIPHON RATING
Subject: HEAD LOSS CALCULATIONS
Engineer: WILSNACK
Sheet No. 1 of 10
Job No. / Program Code: B
Date: 6/7/07 Checked By:

INTAKE SCREEN:



TOTAL BAY WIDTH = 28.6' ±

FROM QASIM (1985), PP 160-1,

$\beta = 1.67$ $b = 6 - \frac{3}{8} = 5\frac{5}{8}$"

$w = 3/8$" $h_v \approx \frac{1^2}{64.4}$ $\theta = \frac{\pi}{2} \Rightarrow \sin\theta = 1$

$$h_l = (1.67)\left[\frac{(3)(8)}{(8)(45)}\right]^{4/3}\left(\frac{1}{64.4}\right) = 0.0007 \text{ FT} \quad (\text{EQ } 8\text{-}2)$$

$-h_l$ IS NEGLIGIBLE

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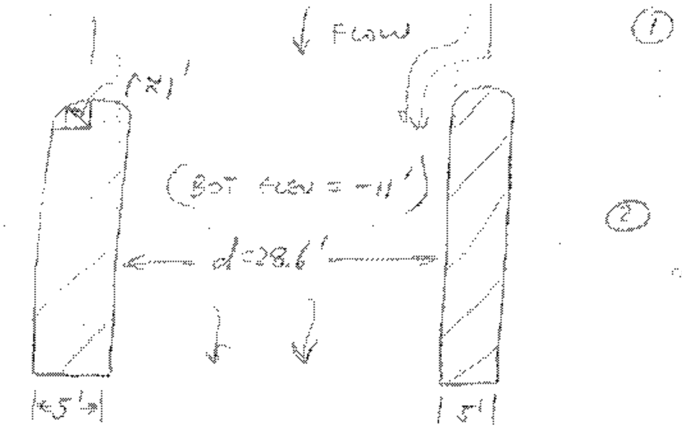
Calculations

Form 90230
Rev.11/97

Project: S-331 SIPHON RATING Sheet No. 2 of 10
Subject: HEAD LOSS CALCULATIONS Job No. / Program Code: 8
Engineer: WILSNACK Date: 4/7/97 Checked By:

HEAD LOSS ENTERING THE PUMP BAY:



$$A_1 \approx (28.6 + 5)\left[5 - (-11)\right] = 537.6 \text{ ft}^2$$

EST. STAGE

$$A_2 = (28.6)\left[5 - (-11)\right] = 457.6 \text{ ft}^2$$

$$\frac{r}{d} = \frac{1}{28.6} = 0.035$$

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Calculations

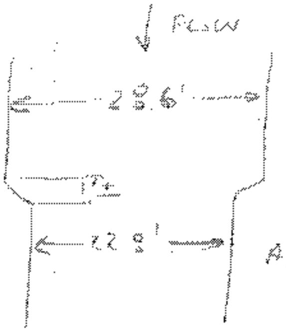
Form #0230
Rev.11/97

Project: S-331 SIPHON RATING Sheet No. 3 of 10
Subject: HEAD LOSS CALCULATIONS Job No. / Program Code: B
Engineer: WILSNACK Date: 4/7/02 Checked By:

FROM FIG. 14-14 OF DS MILLER, K ~ 0.02

$$h_e = K \frac{V_2^2}{2g}$$

CONTRACTION LOSS ENTERING INTAKE CHAMBER:



$A_1 \cong 457.6\ ft^2$

$D_{1EQ} \cong 24\ FT$

$A_2 = (22.8)(2-(-11))$
$= 296.4\ ft^2$

$$D_{2EQ} = \sqrt{\left(\frac{4}{\pi}\right)(296.4)} = 19.4\ FT$$

$$R_{2EQ} = \frac{19.4}{2} = 9.7\ FT$$

$\frac{r}{R_2} = \frac{1}{9.7} \cong 0.1$

$\frac{A_1}{A_2} = \frac{457.6}{296.4} = 1.54$

$\longrightarrow$ FROM FIG 14.14(1) OF DS MILLER, K ~ 0.18

South Florida Water Management District
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Calculations

Form #0230
Rev.11/97

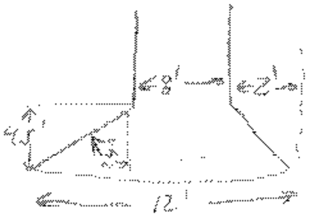
Project: S-331 SIPHON RATING
Sheet No. 4 of 10
Subject: HEAD LOSS CALCULATIONS
Job No. / Program Code: 8
Engineer: WILSNACK
Date: 4/7/07 Checked By:

ENTRANCE LOSS @ PROTRUDING PUMP SUCTION BELL

$K_e \approx 0.8$ FROM DAUGHERTY + FRANZINI; BRATER + KING

TAKE V @ BELL ENTRANCE, $A = \frac{\pi (12)^2}{4} = 36\pi \text{ ft}^2$

CONTRACTION LOSS WITHIN THE SUCTION BELL:



$\frac{r}{d} = \frac{2}{8} = 0.25$

FROM FIG. 14.12 OF DS MILLER, FOR $r/d = 0.25$,

$@ 0°, K \approx 0.54$
$@ 45°, K \approx 0.24$

$\overline{K} = 0.39 \approx 0.4$

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Calculations

Form #0230
Rev.11/97

Project: S-331 SIPHON RATING Sheet No. 5 of 10
Subject: HEAD LOSS CALCULATIONS Job No. / Program Code: R
Engineer: WILSNACK Date: 4/7/97 Checked By:

HEAD LOSS THRU PUMP:

@ G-335, APPROX 26% OF THE INTERNAL PUMP AREA WAS FOUND TO BE DIRECTLY OPEN TO SIPHONS FLOW. USE THIS AS A STARTING % HERE. ADJUST TO MATCH STREAM FLOW DATA.

REFERRING TO FIG. 14.2 OF D.S. MILLER,

$$\frac{d}{D} = \sqrt{0.26} = 0.51 \Rightarrow C_c \approx 0.76$$

$$K_o = \left[1-\left(\frac{d}{D}\right)^2 C_c\right]^2 \left[\frac{1}{(d/D)^4 C_c^2}\right] \quad \text{EQ. 14.3}$$

$$= \left[1-(0.51)^2(0.76)\right]^2 \left[\frac{1}{(0.51)^4(0.76)^2}\right] = 16.47$$

ADJUST d/D, C_c AND K_o TO MAXIMIZE AGREEMENT WITH STREAM FLOW DATA.

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Calculations

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HEAD LOSS THRU DISCHARGE ELBOW:

$A_2 = 92.4\ FT^2$

$D_{2_{EQ}} = 10.85\ FT$

$D_1 = 9.13\ FT$

$A_1 = 65.4\ FT^2$

DETERMINE K_d (DIFFUSER LOSS COEFFICIENT):

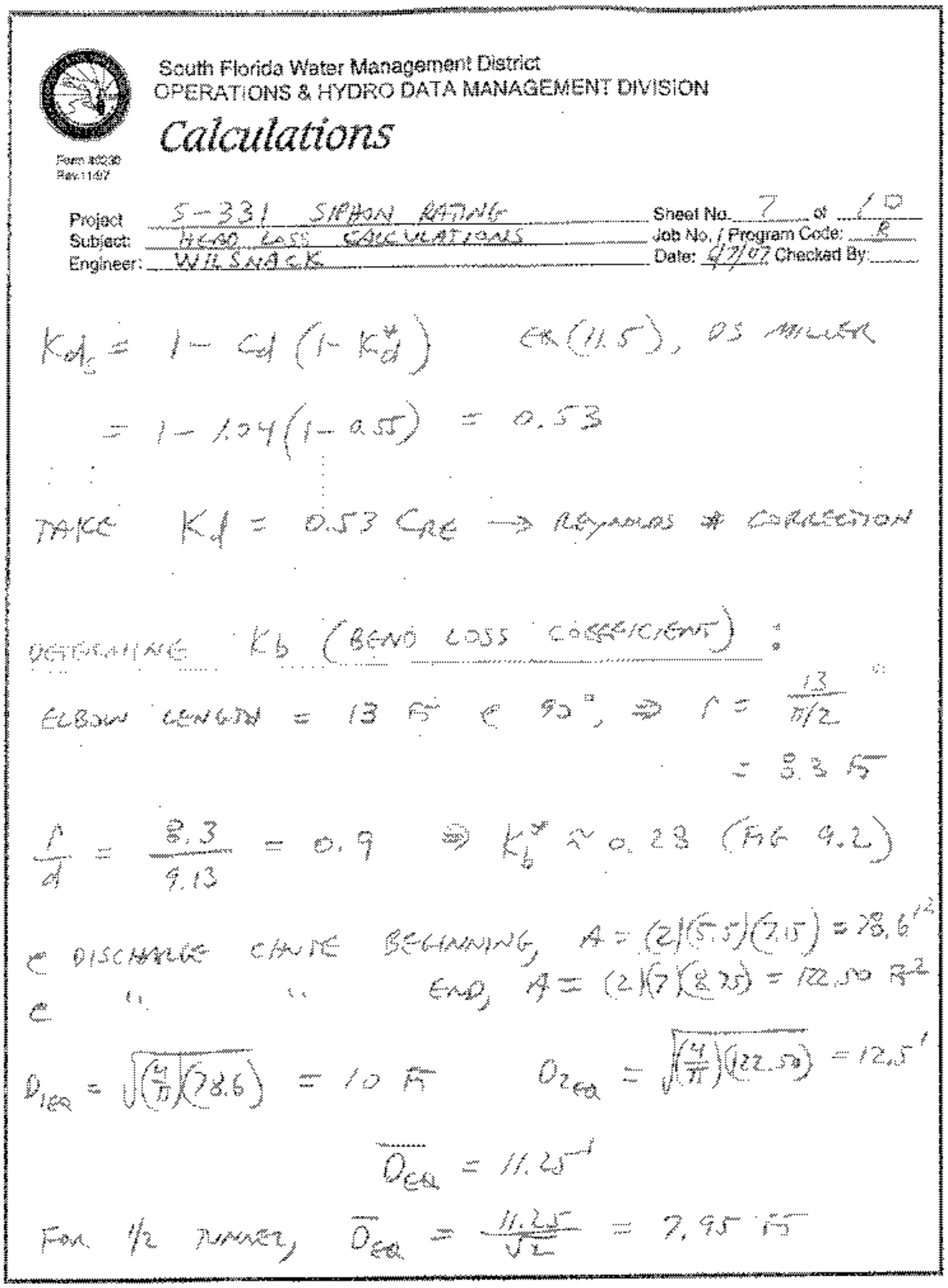
$AR = \frac{92.4}{65.4} = 1.4 \qquad \frac{N}{R_1} = \frac{(13)(2)}{(9.13)} = 2.8$

FROM FIG 11.3 OF DS MILLER, $K_d^* \sim 0.55$

OUTLET TUNNEL LENGTH ≈ 27 FT $\Rightarrow L/D_2 = \frac{27}{10.85}$

$= 2.5$

FROM FIGS 11.6 b, c : $C_d \approx 1.04$



South Florida Water Management District
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$Kd_c = 1 - Cd(1 - K_d^*)$ EQ (11.5), DS MILLER

$= 1 - 1.04(1 - 0.55) = 0.53$

TAKE $K_d = 0.53\ C_{RE}$ → REYNOLDS # CORRECTION

DETERMINE K_b (BEND LOSS COEFFICIENT):

ELBOW LENGTH = 13 FT @ 90°, $\Rightarrow r = \frac{13}{\pi/2}$

$= 8.3$ FT

$\frac{r}{d} = \frac{8.3}{9.13} = 0.9 \Rightarrow K_b^* \approx 0.23$ (FIG 9.2)

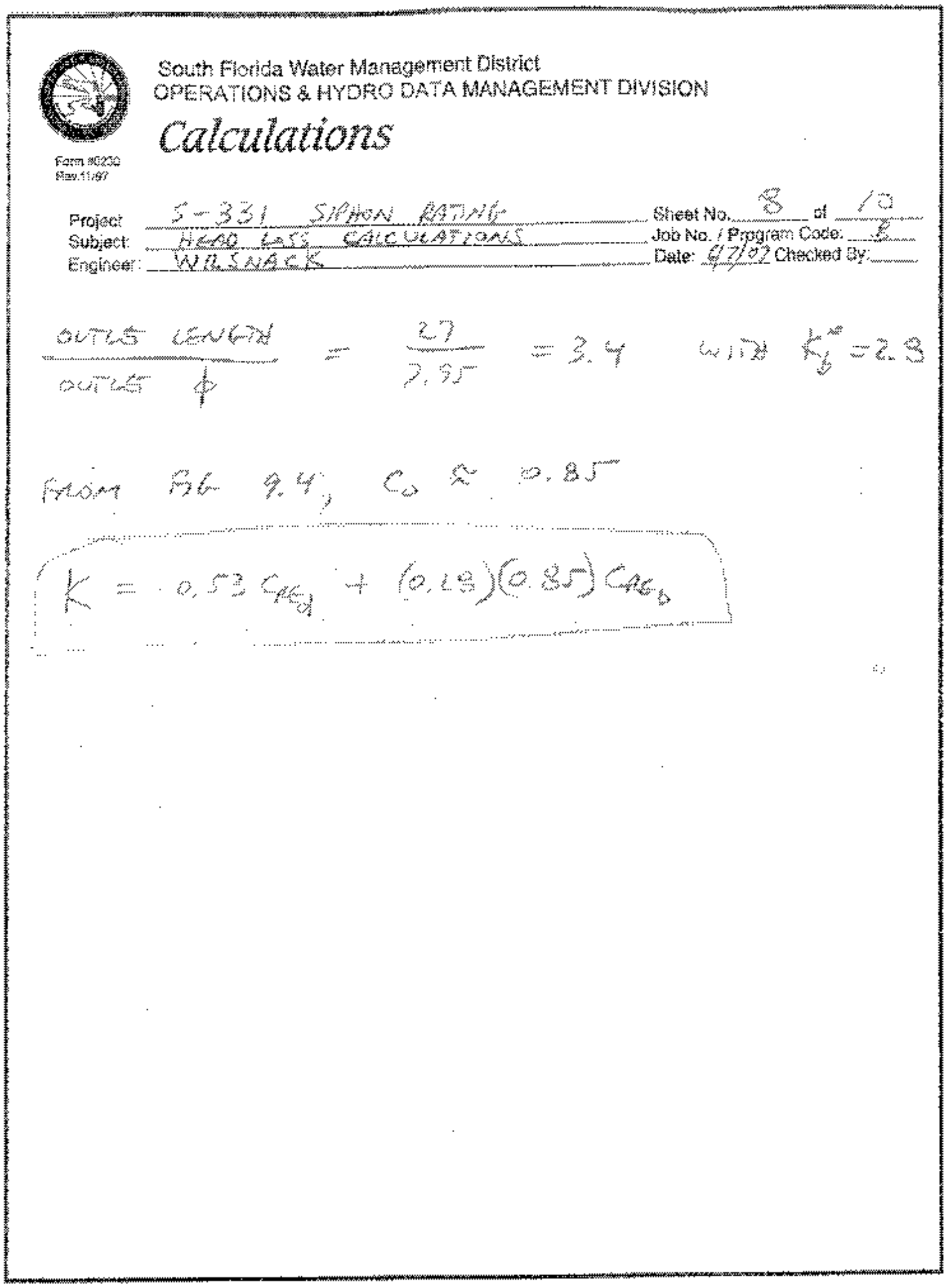
@ DISCHARGE CHUTE BEGINNING, $A = (2)(5.5)(7.15) = 78.6\ ft^2$

@ " " END, $A = (2)(7)(8.75) = 122.50\ ft^2$

$D_{1EQ} = \sqrt{\left(\frac{4}{\pi}\right)(78.6)} = 10$ FT $\quad D_{2EQ} = \sqrt{\left(\frac{4}{\pi}\right)(122.50)} = 12.5'$

$\overline{D_{EQ}} = 11.25'$

FOR 1/2 BARREL, $\overline{D_{EQ}} = \frac{11.25}{\sqrt{2}} = 7.95$ FT



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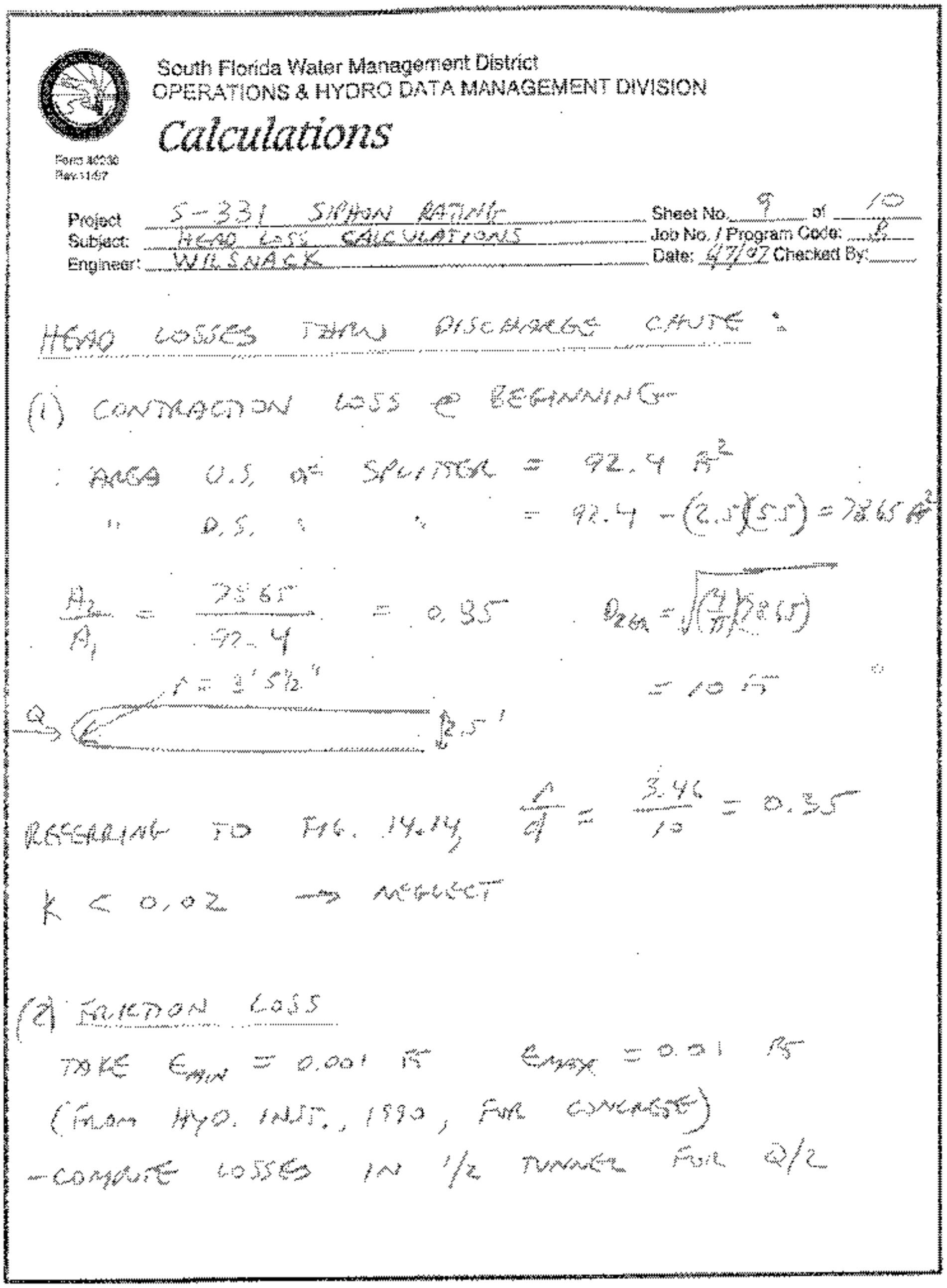
$$\frac{\text{OUTLET LENGTH}}{\text{OUTLET } \phi} = \frac{27}{7.95} = 3.4 \quad \text{WITH } K_b^* = 2.8$$

FROM FIG 9.4; $C_0 \approx 0.85$

$$\boxed{K = 0.53\, C_{AB_a} + (0.18)(0.85)\, C_{AB_b}}$$



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Project: S-331 SIPHON RATING   Sheet No. 9 of 10
Subject: HEAD LOSS CALCULATIONS   Job No. / Program Code: B
Engineer: WILSNACK   Date: 4/7/07 Checked By:

HEAD LOSSES THRU DISCHARGE CHUTE:

(1) CONTRACTION LOSS @ BEGINNING

AREA U.S. OF SPLITTER $= 92.4\ ft^2$

" D.S. " " $= 92.4 - (2.5)(5.5) = 78.65\ ft^2$

$\frac{A_2}{A_1} = \frac{78.65}{92.4} = 0.85$ $D_{eq} = \sqrt{\left(\frac{4}{\pi}\right)(78.65)} = 10\ ft$

$r = 3'5\frac{1}{2}''$

Q →   2.5'

REFERRING TO FIG. 14.14, $\frac{r}{d} = \frac{3.46}{10} = 0.35$

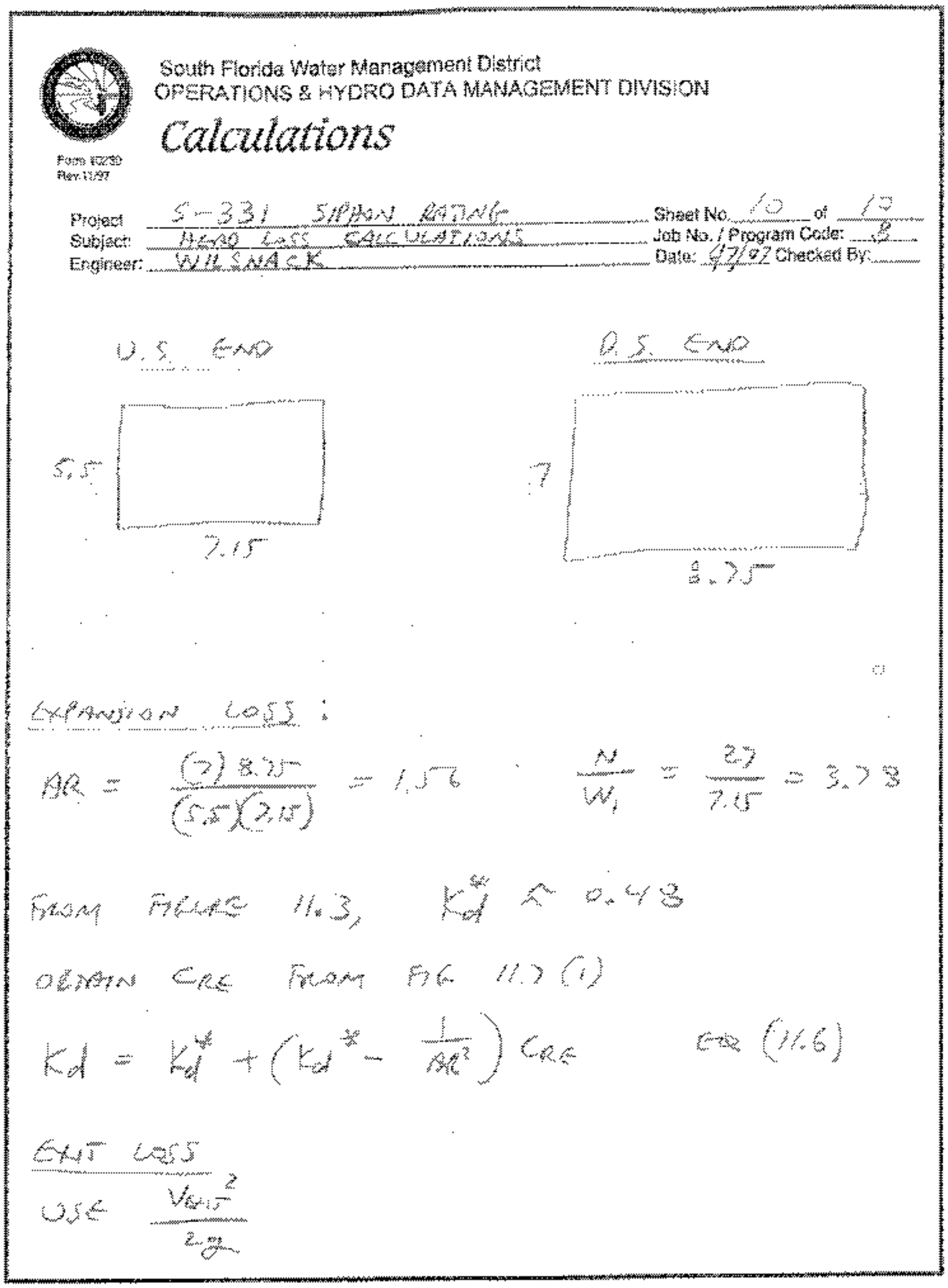
$k < 0.02 \rightarrow$ NEGLECT

(2) FRICTION LOSS

TAKE $\epsilon_{MIN} = 0.001\ ft$ $\epsilon_{MAX} = 0.01\ ft$

(FROM HYD. INST., 1990, FOR CONCRETE)

- COMPUTE LOSSES IN 1/2 TUNNEL FOR Q/2



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U.S. END

5.5

7.15

D.S. END

7

8.75

EXPANSION LOSS:

$$AR = \frac{(7)\,8.75}{(5.5)(7.15)} = 1.56 \qquad \frac{N}{W_1} = \frac{27}{7.15} = 3.78$$

FROM FIGURE 11.3, $K_d^* \approx 0.48$

OBTAIN C_{RE} FROM FIG 11.7 (1)

$$K_d = K_d^* + \left(K_d^* - \frac{1}{AR^2}\right) C_{RE} \qquad \text{EQ } (11.6)$$

ENT LOSS

USE $\dfrac{V_{ENT}^2}{2g}$

Table A1. Minimum head loss calculations

Flow (cfs)	Pump Bay			Intake Chamber			Pump Bell						Pump			Pump Discharge Elbow & Diffuser								Diffuser Discharge Tunnel																		Total Head Loss
	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V_{ecc} (ft/s)	$V^2_{ecc}/2g$ (ft)	entr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	N_R	diffuser C_{rc} (fig 11.X(1))	bend C_{rc} (fig 4.3)	bend C_{rc} (eq 4.3)	K	$KV^2/2g$ (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	init contr loss (ft)	V_b (ft/s)	$V^2_b/2g$ (ft)	N_{Rb}	f_b	h_L	V_d (ft/s)	$V^2_d/2g$ (ft)	N_{Rd}	f_d	h_L	friction hl (ft)	diffuser C_{rc} (fig 11.X(1))	K_d (eq 11.6)	diffuser hl (ft)	exit hl (ft)	Loss
10	0.02	0.00	0.00	0.03	0.00	0.00	0.09	0.00	0.00	0.20	0.00	0.00	0.20	0.00	0.00	0.15	0.00	1.39E+05	1.40	1.10	1.08	1.00	0.00	0.11	0.00	0.00	0.13	0.00	1.98E+04	0.0260	0.000	0.08	0.00	1.59E+04	0.0280	0.000	0.00	0.90	0.54	0.00	0.00	0.00
20	0.04	0.00	0.00	0.07	0.00	0.00	0.18	0.00	0.00	0.40	0.00	0.00	0.40	0.00	0.02	0.31	0.00	2.79E+05	1.25	1.00	1.00	0.90	0.00	0.22	0.00	0.00	0.25	0.00	3.95E+04	0.0220	0.000	0.16	0.00	3.17E+04	0.0240	0.000	0.00	0.65	0.52	0.00	0.00	0.02
30	0.07	0.00	0.00	0.10	0.00	0.00	0.27	0.00	0.00	0.60	0.01	0.00	0.60	0.01	0.03	0.46	0.00	4.18E+05	1.17	1.00	1.00	0.86	0.00	0.32	0.00	0.00	0.38	0.00	5.93E+04	0.0210	0.000	0.24	0.00	4.76E+04	0.0220	0.000	0.00	0.50	0.51	0.00	0.00	0.04
40	0.09	0.00	0.00	0.13	0.00	0.00	0.35	0.00	0.00	0.80	0.01	0.00	0.80	0.01	0.06	0.61	0.01	5.58E+05	1.15	1.00	1.00	0.85	0.00	0.43	0.00	0.00	0.51	0.00	7.91E+04	0.0195	0.000	0.33	0.00	6.35E+04	0.0215	0.000	0.00	0.41	0.51	0.00	0.00	0.07
50	0.11	0.00	0.00	0.17	0.00	0.00	0.44	0.00	0.00	0.99	0.02	0.00	0.99	0.02	0.09	0.76	0.01	6.97E+05	1.10	1.00	1.00	0.82	0.01	0.54	0.00	0.00	0.64	0.01	9.88E+04	0.0190	0.000	0.41	0.00	7.94E+04	0.0200	0.000	0.00	0.33	0.50	0.00	0.00	0.11
60	0.13	0.00	0.00	0.20	0.00	0.00	0.53	0.00	0.00	1.19	0.02	0.01	1.19	0.02	0.14	0.92	0.01	8.37E+05	1.05	1.00	1.00	0.79	0.01	0.65	0.01	0.00	0.76	0.01	1.19E+05	0.0180	0.000	0.49	0.00	9.52E+04	0.0190	0.000	0.00	0.30	0.50	0.00	0.00	0.16
70	0.15	0.00	0.00	0.24	0.00	0.00	0.62	0.01	0.00	1.39	0.03	0.01	1.39	0.03	0.19	1.07	0.02	9.76E+05	1.01	1.00	1.00	0.77	0.01	0.76	0.01	0.00	0.89	0.01	1.38E+05	0.0175	0.000	0.57	0.01	1.11E+05	0.0185	0.000	0.00	0.25	0.50	0.00	0.01	0.22
80	0.17	0.00	0.00	0.27	0.00	0.00	0.71	0.01	0.00	1.59	0.04	0.01	1.59	0.04	0.24	1.22	0.02	1.12E+06	1.00	1.00	1.00	0.77	0.01	0.87	0.01	0.00	1.02	0.02	1.58E+05	0.0172	0.000	0.65	0.01	1.27E+05	0.0177	0.000	0.00	0.22	0.49	0.01	0.01	0.28
90	0.20	0.00	0.00	0.30	0.00	0.00	0.80	0.01	0.01	1.79	0.05	0.01	1.79	0.05	0.31	1.37	0.03	1.26E+06	1.00	1.00	1.00	0.77	0.02	0.97	0.01	0.00	1.14	0.02	1.78E+05	0.0169	0.000	0.73	0.01	1.43E+05	0.0173	0.000	0.00	0.20	0.49	0.01	0.01	0.36
100	0.22	0.00	0.00	0.34	0.00	0.00	0.88	0.01	0.01	1.99	0.06	0.02	1.99	0.06	0.38	1.53	0.04	1.39E+06	1.00	1.00	1.00	0.77	0.02	1.08	0.02	0.00	1.27	0.03	1.98E+05	0.0168	0.000	0.82	0.01	1.59E+05	0.0170	0.000	0.00	0.18	0.49	0.01	0.01	0.44
110	0.24	0.00	0.00	0.37	0.00	0.00	0.97	0.01	0.01	2.19	0.07	0.02	2.19	0.07	0.46	1.68	0.04	1.53E+06	1.00	1.00	1.00	0.77	0.03	1.19	0.02	0.00	1.40	0.03	2.17E+05	0.0165	0.000	0.90	0.01	1.75E+05	0.0169	0.000	0.00	0.16	0.49	0.01	0.01	0.53
120	0.26	0.00	0.00	0.40	0.00	0.00	1.06	0.02	0.01	2.39	0.09	0.03	2.39	0.09	0.55	1.83	0.05	1.67E+06	1.00	1.00	1.00	0.77	0.03	1.30	0.03	0.00	1.53	0.04	2.37E+05	0.0162	0.000	0.98	0.01	1.90E+05	0.0168	0.000	0.00	0.16	0.49	0.01	0.01	0.63
130	0.28	0.00	0.00	0.44	0.00	0.00	1.15	0.02	0.01	2.59	0.10	0.03	2.59	0.10	0.64	1.99	0.06	1.81E+06	1.00	1.00	1.00	0.77	0.04	1.41	0.03	0.00	1.65	0.04	2.57E+05	0.0161	0.000	1.06	0.02	2.06E+05	0.0164	0.000	0.00	0.16	0.49	0.02	0.02	0.74
140	0.31	0.00	0.00	0.47	0.00	0.00	1.24	0.02	0.01	2.79	0.12	0.04	2.79	0.12	0.74	2.14	0.07	1.95E+06	1.00	1.00	1.00	0.77	0.04	1.52	0.04	0.00	1.78	0.05	2.77E+05	0.0158	0.000	1.14	0.02	2.22E+05	0.0163	0.000	0.00	0.16	0.49	0.02	0.02	0.86
150	0.33	0.00	0.00	0.51	0.00	0.00	1.33	0.03	0.02	2.98	0.14	0.04	2.98	0.14	0.85	2.29	0.08	2.09E+06	1.00	1.00	1.00	0.77	0.05	1.62	0.04	0.00	1.91	0.06	2.96E+05	0.0157	0.000	1.22	0.02	2.38E+05	0.0161	0.000	0.00	0.16	0.49	0.02	0.02	0.99
160	0.35	0.00	0.00	0.54	0.00	0.00	1.41	0.03	0.02	3.18	0.16	0.05	3.18	0.16	0.97	2.44	0.09	2.23E+06	1.00	1.00	1.00	0.77	0.05	1.73	0.05	0.00	2.03	0.06	3.16E+05	0.0157	0.000	1.31	0.03	2.54E+05	0.0160	0.000	0.00	0.16	0.49	0.02	0.03	1.13
170	0.37	0.00	0.00	0.57	0.01	0.00	1.50	0.04	0.02	3.38	0.18	0.05	3.38	0.18	1.10	2.60	0.10	2.37E+06	1.00	1.00	1.00	0.77	0.06	1.84	0.05	0.00	2.16	0.07	3.36E+05	0.0155	0.000	1.39	0.03	2.70E+05	0.0159	0.000	0.00	0.16	0.49	0.03	0.03	1.27
180	0.39	0.00	0.00	0.61	0.01	0.00	1.59	0.04	0.02	3.58	0.20	0.06	3.58	0.20	1.23	2.75	0.12	2.51E+06	1.00	1.00	1.00	0.77	0.07	1.95	0.06	0.00	2.29	0.08	3.56E+05	0.0154	0.000	1.47	0.03	2.86E+05	0.0157	0.000	0.00	0.16	0.49	0.03	0.03	1.43
190	0.42	0.00	0.00	0.64	0.01	0.00	1.68	0.04	0.03	3.78	0.22	0.07	3.78	0.22	1.37	2.90	0.13	2.65E+06	1.00	1.00	1.00	0.77	0.08	2.06	0.07	0.00	2.42	0.09	3.75E+05	0.0153	0.000	1.55	0.04	3.02E+05	0.0156	0.000	0.00	0.16	0.49	0.03	0.04	1.59
200	0.44	0.00	0.00	0.67	0.01	0.00	1.77	0.05	0.03	3.98	0.25	0.07	3.98	0.25	1.52	3.05	0.14	2.79E+06	1.00	1.00	1.00	0.77	0.08	2.16	0.07	0.00	2.54	0.10	3.95E+05	0.0152	0.000	1.63	0.04	3.17E+05	0.0155	0.000	0.00	0.16	0.49	0.04	0.04	1.76
210	0.46	0.00	0.00	0.71	0.01	0.00	1.86	0.05	0.03	4.18	0.27	0.08	4.18	0.27	1.67	3.21	0.16	2.93E+06	1.00	1.00	1.00	0.77	0.09	2.27	0.08	0.00	2.67	0.11	4.15E+05	0.0152	0.000	1.71	0.05	3.33E+05	0.0153	0.000	0.01	0.16	0.49	0.04	0.05	1.94
220	0.48	0.00	0.00	0.74	0.01	0.00	1.95	0.06	0.04	4.38	0.30	0.09	4.38	0.30	1.84	3.36	0.18	3.07E+06	1.00	1.00	1.00	0.77	0.10	2.38	0.09	0.00	2.80	0.12	4.35E+05	0.0151	0.000	1.80	0.05	3.49E+05	0.0152	0.000	0.01	0.16	0.49	0.05	0.05	2.13
230	0.50	0.00	0.00	0.78	0.01	0.00	2.03	0.06	0.04	4.58	0.33	0.10	4.58	0.33	2.01	3.51	0.19	3.21E+06	1.00	1.00	1.00	0.77	0.11	2.49	0.10	0.00	2.92	0.13	4.55E+05	0.0150	0.000	1.88	0.06	3.65E+05	0.0152	0.000	0.01	0.16	0.49	0.05	0.06	2.33
235	0.51	0.00	0.00	0.79	0.01	0.00	2.08	0.07	0.04	4.68	0.34	0.10	4.68	0.34	2.10	3.59	0.20	3.28E+06	1.00	1.00	1.00	0.77	0.12	2.54	0.10	0.00	2.99	0.14	4.64E+05	0.0150	0.000	1.92	0.06	3.73E+05	0.0151	0.000	0.01	0.16	0.49	0.05	0.06	2.43

Table A2. Average head loss calculations

Flow (cfs)	Pump Bay			Intake Chamber			Pump Bell						Pump			Pump Discharge Elbow & Diffuser								Diffuser Discharge Tunnel																		Total Head Loss	TSH, Existing Rating
	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V_{ecc} (ft/s)	$V^2_{ecc}/2g$ (ft)	entr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	N_R	diffuser C_{rc} (fig 11.X(1))	bend C_{rc} (fig 4.3)	bend C_{rc} (eq 4.3)	K	$KV^2/2g$ (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	init contr loss (ft)	V_b (ft/s)	$V^2_b/2g$ (ft)	N_{Rb}	f_b	h_bL	V_d (ft/s)	$V^2_d/2g$ (ft)	N_{Rd}	f_d	h_dL	friction hl (ft)	diffuser C_{rc} (fig 11.X(1))	K_d (eq 11.6)	diffuser hl (ft)	exit hl (ft)	Loss	
10	0.02	0.00	0.00	0.03	0.00	0.00	0.09	0.00	0.00	0.20	0.00	0.00	0.20	0.00	0.01	0.15	0.00	1.39E+05	1.40	1.10	1.08	1.00	0.00	0.11	0.00	0.00	0.13	0.00	1.98E+04	0.027	0.000	0.08	0.00	1.59E+04	0.029	0.000	0.00	0.90	0.54	0.00	0.00	0.01	0.01
20	0.04	0.00	0.00	0.07	0.00	0.00	0.18	0.00	0.00	0.40	0.00	0.00	0.40	0.00	0.02	0.31	0.00	2.79E+05	1.25	1.00	1.00	0.90	0.00	0.22	0.00	0.00	0.25	0.00	3.95E+04	0.024	0.000	0.16	0.00	3.17E+04	0.025	0.000	0.00	0.65	0.52	0.00	0.00	0.02	0.02
30	0.07	0.00	0.00	0.10	0.00	0.00	0.27	0.00	0.00	0.60	0.01	0.00	0.60	0.01	0.05	0.46	0.00	4.18E+05	1.17	1.00	1.00	0.86	0.00	0.32	0.00	0.00	0.38	0.00	5.93E+04	0.023	0.000	0.24	0.00	4.76E+04	0.024	0.000	0.00	0.50	0.51	0.00	0.00	0.05	0.04
40	0.09	0.00	0.00	0.13	0.00	0.00	0.35	0.00	0.00	0.80	0.01	0.00	0.80	0.01	0.08	0.61	0.01	5.58E+05	1.15	1.00	1.00	0.85	0.00	0.43	0.00	0.00	0.51	0.00	7.91E+04	0.022	0.000	0.33	0.00	6.35E+04	0.023	0.000	0.00	0.41	0.51	0.00	0.00	0.09	0.07
50	0.11	0.00	0.00	0.17	0.00	0.00	0.44	0.00	0.00	0.99	0.02	0.01	0.99	0.02	0.13	0.76	0.01	6.97E+05	1.10	1.00	1.00	0.82	0.01	0.54	0.00	0.00	0.64	0.01	9.88E+04	0.021	0.000	0.41	0.00	7.94E+04	0.022	0.000	0.00	0.33	0.50	0.00	0.00	0.15	0.10
60	0.13	0.00	0.00	0.20	0.00	0.00	0.53	0.00	0.00	1.19	0.02	0.01	1.19	0.02	0.18	0.92	0.01	8.37E+05	1.05	1.00	1.00	0.79	0.01	0.65	0.01	0.00	0.76	0.01	1.19E+05	0.020	0.000	0.49	0.00	9.52E+04	0.021	0.000	0.00	0.30	0.50	0.00	0.00	0.21	0.16
70	0.15	0.00	0.00	0.24	0.00	0.00	0.62	0.01	0.00	1.39	0.03	0.01	1.39	0.03	0.25	1.07	0.02	9.76E+05	1.01	1.00	1.00	0.77	0.01	0.76	0.01	0.00	0.89	0.01	1.38E+05	0.020	0.000	0.57	0.01	1.11E+05	0.021	0.000	0.00	0.25	0.50	0.01	0.01	0.29	0.22
80	0.17	0.00	0.00	0.27	0.00	0.00	0.71	0.01	0.01	1.59	0.04	0.02	1.59	0.04	0.32	1.22	0.02	1.12E+06	1.00	1.00	1.00	0.77	0.02	0.87	0.01	0.00	1.02	0.02	1.58E+05	0.020	0.000	0.65	0.01	1.27E+05	0.020	0.000	0.00	0.22	0.49	0.01	0.01	0.37	0.31
90	0.20	0.00	0.00	0.30	0.00	0.00	0.80	0.01	0.01	1.79	0.05	0.02	1.79	0.05	0.41	1.37	0.03	1.26E+06	1.00	1.00	1.00	0.77	0.02	0.97	0.01	0.00	1.14	0.02	1.78E+05	0.020	0.000	0.73	0.01	1.43E+05	0.020	0.000	0.00	0.20	0.49	0.01	0.01	0.47	0.40
100	0.22	0.00	0.00	0.34	0.00	0.00	0.88	0.01	0.01	1.99	0.06	0.02	1.99	0.06	0.51	1.53	0.04	1.39E+06	1.00	1.00	1.00	0.77	0.03	1.08	0.02	0.00	1.27	0.03	1.98E+05	0.020	0.000	0.82	0.01	1.59E+05	0.020	0.000	0.00	0.18	0.49	0.01	0.01	0.58	0.53
110	0.24	0.00	0.00	0.37	0.00	0.00	0.97	0.01	0.01	2.19	0.07	0.03	2.19	0.07	0.61	1.68	0.04	1.53E+06	1.00	1.00	1.00	0.77	0.03	1.19	0.02	0.00	1.40	0.03	2.17E+05	0.019	0.000	0.90	0.01	1.75E+05	0.020	0.000	0.00	0.16	0.49	0.02	0.01	0.71	0.65
120	0.26	0.00	0.00	0.40	0.00	0.00	1.06	0.02	0.01	2.39	0.09	0.04	2.39	0.09	0.73	1.83	0.05	1.67E+06	1.00	1.00	1.00	0.77	0.04	1.30	0.03	0.00	1.53	0.04	2.37E+05	0.019	0.000	0.98	0.01	1.90E+05	0.019	0.000	0.00	0.16	0.49	0.02	0.01	0.84	0.80
130	0.28	0.00	0.00	0.44	0.00	0.00	1.15	0.02	0.02	2.59	0.10	0.04	2.59	0.10	0.86	1.99	0.06	1.81E+06	1.00	1.00	1.00	0.77	0.05	1.41	0.03	0.00	1.65	0.04	2.57E+05	0.019	0.000	1.06	0.02	2.06E+05	0.019	0.000	0.00	0.16	0.49	0.02	0.02	0.99	0.98
140	0.31	0.00	0.00	0.47	0.00	0.00	1.24	0.02	0.02	2.79	0.12	0.05	2.79	0.12	0.99	2.14	0.07	1.95E+06	1.00	1.00	1.00	0.77	0.05	1.52	0.04	0.00	1.78	0.05	2.77E+05	0.019	0.000	1.14	0.02	2.22E+05	0.019	0.000	0.00	0.16	0.49	0.02	0.02	1.14	1.15
150	0.33	0.00	0.00	0.51	0.00	0.00	1.33	0.03	0.02	2.98	0.14	0.06	2.98	0.14	1.14	2.29	0.08	2.09E+06	1.00	1.00	1.00	0.77	0.06	1.62	0.04	0.00	1.91	0.06	2.96E+05	0.019	0.000	1.22	0.02	2.38E+05	0.019	0.000	0.00	0.16	0.49	0.03	0.02	1.31	1.36
160	0.35	0.00	0.00	0.54	0.00	0.00	1.41	0.03	0.02	3.18	0.16	0.06	3.18	0.16	1.30	2.44	0.09	2.23E+06	1.00	1.00	1.00	0.77	0.07	1.73	0.05	0.00	2.03	0.06	3.16E+05	0.019	0.000	1.31	0.03	2.54E+05	0.019	0.000	0.00	0.16	0.49	0.03	0.03	1.49	1.60
170	0.37	0.00	0.00	0.57	0.01	0.00	1.50	0.04	0.03	3.38	0.18	0.07	3.38	0.18	1.46	2.60	0.10	2.37E+06	1.00	1.00	1.00	0.77	0.08	1.84	0.05	0.00	2.16	0.07	3.36E+05	0.019	0.000	1.39	0.03	2.70E+05	0.019	0.000	0.00	0.16	0.49	0.04	0.03	1.69	1.84
180	0.39	0.00	0.00	0.61	0.01	0.00	1.59	0.04	0.03	3.58	0.20	0.08	3.58	0.20	1.64	2.75	0.12	2.51E+06	1.00	1.00	1.00	0.77	0.09	1.95	0.06	0.00	2.29	0.08	3.56E+05	0.019	0.000	1.47	0.03	2.86E+05	0.019	0.000	0.00	0.16	0.49	0.04	0.03	1.89	2.12
190	0.42	0.00	0.00	0.64	0.01	0.00	1.68	0.04	0.04	3.78	0.22	0.09	3.78	0.22	1.83	2.90	0.13	2.65E+06	1.00	1.00	1.00	0.77	0.10	2.06	0.07	0.00	2.42	0.09	3.75E+05	0.019	0.000	1.55	0.04	3.02E+05	0.019	0.000	0.00	0.16	0.49	0.04	0.04	2.11	2.40
200	0.44	0.00	0.00	0.67	0.01	0.00	1.77	0.05	0.04	3.98	0.25	0.10	3.98	0.25	2.02	3.05	0.14	2.79E+06	1.00	1.00	1.00	0.77	0.11	2.16	0.07	0.00	2.54	0.10	3.95E+05	0.019	0.000	1.63	0.04	3.17E+05	0.018	0.000	0.01	0.16	0.49	0.05	0.04	2.33	2.73
210	0.46	0.00	0.00	0.71	0.01	0.00	1.86	0.05	0.04	4.18	0.27	0.11	4.18	0.27	2.23	3.21	0.16	2.93E+06	1.00	1.00	1.00	0.77	0.12	2.27	0.08	0.00	2.67	0.11	4.15E+05	0.019	0.000	1.71	0.05	3.33E+05	0.018	0.000	0.01	0.16	0.49	0.05	0.05	2.57	3.08
220	0.48	0.00	0.00	0.74	0.01	0.00	1.95	0.06	0.05	4.38	0.30	0.12	4.38	0.30	2.45	3.36	0.18	3.07E+06	1.00	1.00	1.00	0.77	0.13	2.38	0.09	0.00	2.80	0.12	4.35E+05	0.019	0.000	1.80	0.05	3.49E+05	0.018	0.000	0.01	0.16	0.49	0.06	0.05	2.82	3.42
230	0.50	0.00	0.00	0.78	0.01	0.00	2.03	0.06	0.05	4.58	0.33	0.13	4.58	0.33	2.68	3.51	0.19	3.21E+06	1.00	1.00	1.00	0.77	0.15	2.49	0.10	0.00	2.92	0.13	4.55E+05	0.019	0.000	1.88	0.06	3.65E+05	0.018	0.000	0.01	0.16	0.49	0.07	0.06	3.08	3.80
235	0.51	0.00	0.00	0.79	0.01	0.00	2.08	0.07	0.05	4.68	0.34	0.14	4.68	0.34	2.80	3.59	0.20	3.28E+06	1.00	1.00	1.00	0.77	0.15	2.54	0.10	0.00	2.99	0.14	4.64E+05	0.019	0.000	1.92	0.06	3.73E+05	0.018	0.000	0.01	0.16	0.49	0.07	0.06	3.22	4.00

Table A3. Maximum head loss calculations

Flow (cfs)	Pump Bay			Intake Chamber			Pump Bell						Pump			Pump Discharge Elbow & Diffuser								Diffuser Discharge Tunnel																		Total Head Loss
	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V (ft/s)	$V^2/2g$ (ft)	entr loss (ft)	V_{mouth} (ft/s)	$V^2_{mouth}/2g$ (ft)	entr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_p (ft/s)	$V^2_p/2g$ (ft)	contr loss (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	N_R	diffuser C_K (Eq 11.70)	bend C_K (Eq 1.1)	bend C_K (eq 1.1)	K	$K V^2_1/2g$ (ft)	V_1 (ft/s)	$V^2_1/2g$ (ft)	init contr loss (ft)	V_o (ft/s)	$V^2_o/2g$ (ft)	N_{Ro}	f_o	hf/L	V_d (ft/s)	$V^2_d/2g$ (ft)	N_{Rd}	f_d	hf/L	friction loss (ft)	diffuser C_K (Eq 11.70)	K_D (eq 11.6)	diffuser loss (ft)	exit loss (ft)	
10	0.02	0.00	0.00	0.03	0.00	0.00	0.09	0.00	0.00	0.20	0.00	0.00	0.20	0.00	0.01	0.15	0.00	1.39E+05	1.40	1.10	1.08	1.00	0.00	0.11	0.00	0.00	0.13	0.00	1.98E+04	0.0285	0.000	0.08	0.00	1.59E+04	0.0300	0.000	0.00	0.90	0.54	0.00	0.00	0.01
20	0.04	0.00	0.00	0.07	0.00	0.00	0.18	0.00	0.00	0.40	0.00	0.00	0.40	0.00	0.03	0.31	0.00	2.79E+05	1.25	1.00	1.00	0.90	0.00	0.22	0.00	0.00	0.25	0.00	3.95E+04	0.0260	0.000	0.16	0.00	3.17E+04	0.0265	0.000	0.00	0.65	0.52	0.00	0.00	0.03
30	0.07	0.00	0.00	0.10	0.00	0.00	0.27	0.00	0.00	0.60	0.01	0.00	0.60	0.01	0.06	0.46	0.00	4.18E+05	1.17	1.00	1.00	0.86	0.00	0.32	0.00	0.00	0.38	0.00	5.93E+04	0.0245	0.000	0.24	0.00	4.76E+04	0.0250	0.000	0.00	0.50	0.51	0.00	0.00	0.07
40	0.09	0.00	0.00	0.13	0.00	0.00	0.35	0.00	0.00	0.80	0.01	0.00	0.80	0.01	0.10	0.61	0.01	5.58E+05	1.15	1.00	1.00	0.85	0.01	0.43	0.00	0.00	0.51	0.00	7.91E+04	0.0240	0.000	0.33	0.00	6.35E+04	0.0243	0.000	0.00	0.43	0.51	0.00	0.00	0.12
50	0.11	0.00	0.00	0.17	0.00	0.00	0.44	0.00	0.00	0.99	0.02	0.01	0.99	0.02	0.16	0.76	0.01	6.97E+05	1.10	1.00	1.00	0.82	0.01	0.54	0.00	0.00	0.64	0.01	9.88E+04	0.0235	0.000	0.41	0.00	7.94E+04	0.0235	0.000	0.00	0.37	0.50	0.00	0.00	0.18
60	0.13	0.00	0.00	0.20	0.00	0.00	0.53	0.00	0.00	1.19	0.02	0.01	1.19	0.02	0.23	0.92	0.01	8.37E+05	1.05	1.00	1.00	0.79	0.01	0.65	0.01	0.00	0.76	0.01	1.19E+05	0.0227	0.000	0.49	0.00	9.52E+04	0.0233	0.000	0.00	0.30	0.50	0.01	0.00	0.26
70	0.15	0.00	0.00	0.24	0.00	0.00	0.62	0.01	0.01	1.39	0.03	0.02	1.39	0.03	0.31	1.07	0.02	9.76E+05	1.01	1.00	1.00	0.77	0.02	0.76	0.01	0.00	0.89	0.01	1.38E+05	0.0226	0.000	0.57	0.01	1.11E+05	0.0230	0.000	0.00	0.25	0.50	0.01	0.01	0.36
80	0.17	0.00	0.00	0.27	0.00	0.00	0.71	0.01	0.01	1.59	0.04	0.02	1.59	0.04	0.40	1.22	0.02	1.12E+06	1.00	1.00	1.00	0.77	0.02	0.87	0.01	0.00	1.02	0.02	1.58E+05	0.0226	0.000	0.65	0.01	1.27E+05	0.0228	0.000	0.00	0.22	0.49	0.01	0.01	0.46
90	0.20	0.00	0.00	0.30	0.00	0.00	0.80	0.01	0.01	1.79	0.05	0.02	1.79	0.05	0.51	1.37	0.03	1.26E+06	1.00	1.00	1.00	0.77	0.03	0.97	0.01	0.00	1.14	0.02	1.78E+05	0.0225	0.000	0.73	0.01	1.43E+05	0.0225	0.000	0.00	0.20	0.49	0.01	0.01	0.59
100	0.22	0.00	0.00	0.34	0.00	0.00	0.88	0.01	0.01	1.99	0.06	0.03	1.99	0.06	0.63	1.53	0.04	1.39E+06	1.00	1.00	1.00	0.77	0.03	1.08	0.02	0.00	1.27	0.03	1.98E+05	0.0225	0.000	0.82	0.01	1.59E+05	0.0224	0.000	0.00	0.18	0.49	0.02	0.01	0.73
110	0.24	0.00	0.00	0.37	0.00	0.00	0.97	0.01	0.01	2.19	0.07	0.04	2.19	0.07	0.77	1.68	0.04	1.53E+06	1.00	1.00	1.00	0.77	0.04	1.19	0.02	0.00	1.40	0.03	2.17E+05	0.0225	0.000	0.90	0.01	1.75E+05	0.0223	0.000	0.00	0.16	0.49	0.02	0.01	0.88
120	0.26	0.00	0.00	0.40	0.00	0.00	1.06	0.02	0.02	2.39	0.09	0.04	2.39	0.09	0.91	1.83	0.05	1.67E+06	1.00	1.00	1.00	0.77	0.05	1.30	0.03	0.00	1.53	0.04	2.37E+05	0.0224	0.000	0.98	0.01	1.90E+05	0.0221	0.000	0.00	0.16	0.49	0.02	0.01	1.05
130	0.28	0.00	0.00	0.44	0.00	0.00	1.15	0.02	0.02	2.59	0.10	0.05	2.59	0.10	1.07	1.99	0.06	1.81E+06	1.00	1.00	1.00	0.77	0.06	1.41	0.03	0.00	1.65	0.04	2.57E+05	0.0224	0.000	1.06	0.02	2.06E+05	0.0220	0.000	0.00	0.16	0.49	0.03	0.02	1.23
140	0.31	0.00	0.00	0.47	0.00	0.00	1.24	0.02	0.02	2.79	0.12	0.06	2.79	0.12	1.24	2.14	0.07	1.95E+06	1.00	1.00	1.00	0.77	0.07	1.52	0.04	0.00	1.78	0.05	2.77E+05	0.0224	0.000	1.14	0.02	2.22E+05	0.0219	0.000	0.00	0.16	0.49	0.03	0.02	1.42
150	0.33	0.00	0.00	0.51	0.00	0.00	1.33	0.03	0.03	2.98	0.14	0.07	2.98	0.14	1.42	2.29	0.08	2.09E+06	1.00	1.00	1.00	0.77	0.08	1.62	0.04	0.00	1.91	0.06	2.96E+05	0.0224	0.000	1.22	0.02	2.38E+05	0.0218	0.000	0.00	0.16	0.49	0.03	0.02	1.63
160	0.35	0.00	0.00	0.54	0.00	0.00	1.41	0.03	0.03	3.18	0.16	0.08	3.18	0.16	1.62	2.44	0.09	2.23E+06	1.00	1.00	1.00	0.77	0.09	1.73	0.05	0.00	2.03	0.06	3.16E+05	0.0224	0.000	1.31	0.03	2.54E+05	0.0218	0.000	0.00	0.16	0.49	0.04	0.03	1.86
170	0.37	0.00	0.00	0.57	0.01	0.00	1.50	0.04	0.04	3.38	0.18	0.09	3.38	0.18	1.83	2.60	0.10	2.37E+06	1.00	1.00	1.00	0.77	0.10	1.84	0.05	0.00	2.16	0.07	3.36E+05	0.0223	0.000	1.39	0.03	2.70E+05	0.0217	0.000	0.00	0.16	0.49	0.04	0.03	2.10
180	0.39	0.00	0.00	0.61	0.01	0.00	1.59	0.04	0.04	3.58	0.20	0.10	3.58	0.20	2.05	2.75	0.12	2.51E+06	1.00	1.00	1.00	0.77	0.11	1.95	0.06	0.00	2.29	0.08	3.56E+05	0.0223	0.000	1.47	0.03	2.86E+05	0.0216	0.000	0.01	0.16	0.49	0.05	0.03	2.35
190	0.42	0.00	0.00	0.64	0.01	0.00	1.68	0.04	0.04	3.78	0.22	0.11	3.78	0.22	2.28	2.90	0.13	2.65E+06	1.00	1.00	1.00	0.77	0.13	2.06	0.07	0.00	2.42	0.09	3.75E+05	0.0223	0.000	1.55	0.04	3.02E+05	0.0215	0.000	0.01	0.16	0.49	0.06	0.04	2.62
200	0.44	0.00	0.00	0.67	0.01	0.00	1.77	0.05	0.05	3.98	0.25	0.12	3.98	0.25	2.53	3.05	0.14	2.79E+06	1.00	1.00	1.00	0.77	0.14	2.16	0.07	0.00	2.54	0.10	3.95E+05	0.0223	0.000	1.63	0.04	3.17E+05	0.0212	0.000	0.01	0.16	0.49	0.06	0.04	2.90
210	0.46	0.00	0.00	0.71	0.01	0.00	1.86	0.05	0.05	4.18	0.27	0.14	4.18	0.27	2.79	3.21	0.16	2.93E+06	1.00	1.00	1.00	0.77	0.15	2.27	0.08	0.00	2.67	0.11	4.15E+05	0.0223	0.000	1.71	0.05	3.33E+05	0.0212	0.000	0.01	0.16	0.49	0.07	0.05	3.20
220	0.48	0.00	0.00	0.74	0.01	0.00	1.95	0.06	0.06	4.38	0.30	0.15	4.38	0.30	3.06	3.36	0.18	3.07E+06	1.00	1.00	1.00	0.77	0.17	2.38	0.09	0.00	2.80	0.12	4.35E+05	0.0223	0.000	1.80	0.05	3.49E+05	0.0211	0.000	0.01	0.16	0.49	0.08	0.05	3.51
230	0.50	0.00	0.00	0.78	0.01	0.00	2.03	0.06	0.06	4.58	0.33	0.16	4.58	0.33	3.35	3.51	0.19	3.21E+06	1.00	1.00	1.00	0.77	0.18	2.49	0.10	0.00	2.92	0.13	4.55E+05	0.0223	0.000	1.88	0.06	3.65E+05	0.0211	0.000	0.01	0.16	0.49	0.08	0.06	3.84
235	0.51	0.00	0.00	0.79	0.01	0.00	2.08	0.07	0.07	4.68	0.34	0.17	4.68	0.34	3.49	3.59	0.20	3.28E+06	1.00	1.00	1.00	0.77	0.19	2.54	0.10	0.00	2.99	0.14	4.64E+05	0.0223	0.001	1.92	0.06	3.73E+05	0.0211	0.000	0.01	0.16	0.49	0.09	0.06	4.01