GUIDELINES FOR HYDRAULIC RATING ANALYSES OF PUMPING PLANTS

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TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

The author wishes to express appreciation to Hua Li and Claudia Manriquez who each played a key role in successfully applying the flow rating analysis procedures discussed in this report to many pump stations throughout the District.

DEFINITIONS

Acronyms

NLIN	Nonlinear regression procedure in SAS software
TDH	Total dynamic head
TSH	Total static head
SOP	Standard Operating Procedure
FSI	Formed Suction Intake

EXECUTIVE SUMMARY

A standard operating procedure for the hydraulic rating analyses of pump stations is presented in this report. This procedure has been applied in whole or part to a number of pump stations that vary in size, complexity and functionality. The general procedure is comprised of the following steps:

1. Assessment of the facility layout and site conditions.
2. Acquisition of engineering data and drawings.
3. Evaluation of engineering data and pump station properties.
4. Determine the relationship between flow and total static head (TSH).
5. Determine the rating equation parameters.
6. Perform an impact analysis.
7. Document the rating analysis in an appropriate format.

Depending on the characteristics of the pump station and the available information, not all of the above steps will necessarily need to be performed. Nonetheless, they should serve as comprehensive guidelines to ensure that the required facets of a rating analysis are accounted for.

PREFACE

The trade names of various products and software are used at certain places within this document for illustrative purposes or as examples only. *Their use does not imply endorsement by the South Florida Water Management District nor does it imply criticism of similar products or software not mentioned*.

1.0 INTRODUCTION

1.1 General Characteristics of SFWMD Pump Stations

Most of the pumps installed at District pump stations are of the centrifugal type, vertical-axial flow design. A schematic depicting this type of pump installation is shown in Figure 1a. Generally, a portion of the pump unit is submerged in a wet well located within the intake works while its outlet is unsubmerged. The pump unit itself is illustrated conceptually in Figure 1b. The impellers are sited at the lower end of the pump casing and are connected through a vertical line shaft to either a variable speed motor (usually powered by diesel fuel) or a constant speed motor (usually powered by electricity). The impellers accelerate the water through the pump casing. A prototype of a large capacity pump is shown in Figure 1c. Examples of pump stations utilizing these types of pumps include S-382, S-319 and G-335.

In contrast, some of the smaller, newer pump stations utilize submersible centrifugal pumps installed within the wet well, where the entire pump unit is submerged. This type of design is also common to municipal pump stations used for sewage and storm water transmission. Examples include S-390 and S-385.

Jones et al (2006) provide some excellent comprehensive discussions on the design and operation of centrifugal pumps along with the engineering principles associated with pump operation and pressure flows in pipes. Those wishing to explore additional background information on these subjects are encouraged to review this reference.

1.2 Purpose of this Standard Operating Procedure

The purpose of this Standard Operating Procedure (SOP) is to: (i) provide a framework for conducting pump station rating analyses by outlining the primary tasks involved; (ii) help ensure consistency (to the extent warranted) in the overall approach to performing a hydraulic rating analysis as well as in the specific methodologies employed to complete the various tasks; and (iii) establish minimum expectations for the quality of the results. It should be emphasized that this SOP is *not* to be construed as a cook book for carrying out rating analyses of pump stations. In carrying out such a rating analysis, the hydraulic engineer may likely encounter circumstances or issues not addressed in this document. For example, an unusual design may either necessitate the use of methodologies or procedures not included here or render invalid those that are. Sound engineering judgment should always be exercised throughout the entire effort since deviations from this SOP may sometimes be necessary.

2.0 REQUIRED TASKS

There are essentially seven primary tasks associated with a rating analysis of a pump station. They can be stated as follows:

1. Assessment of the facility layout and site conditions.
2. Acquisition of engineering data and drawings.
3. Evaluation of engineering data and pump station properties.
4. Determine the relationship between flow and total static head (TSH).
5. Determine the rating equation parameters.
6. Perform an impact analysis.

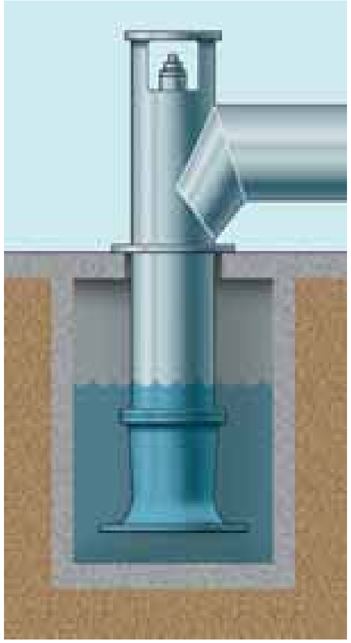

Figure 1a. General schematic of a vertical axial-flow pump installation (courtesy of the FlowServe Corporation)

Figure 1b. Conceptual design of a vertical axial-flow pump (courtesy of the FlowServe Corporation)

Figure 1c. An example of a large capacity vertical axial-flow pump (courtesy of the FlowServe Corporation)

7. Document the rating analysis in an appropriate format.

Not all of these tasks will necessarily need to be performed during a rating analysis. For example, a new pump station will not have an existing rating equation, so in this case task 6 would not be carried out.

2.1 Task 1. Assessment of Facility Layout and Site Conditions

The first step is to become familiar with the configuration of the pump station facilities and general site conditions. The engineer performing the rating analysis should first review a detailed aerial images or site photographs that provide a clear view of the source and receiving water bodies, the alignment of the station intake and discharge works with these water bodies and the locations of all relevant stage monitoring stations. Afterward, a field visit to the facility is recommended.

In particular, one should identify any potential problems with or limitations of flow measurements taken at this site. Also noted should be any flow obstructions between the location of the head water monitoring station and the intake works or between the discharge point and the tail water monitoring location. Finally, try to judge whether or not the stage receiving water body may be sensitive to the discharge rate. All of this will help the engineer to anticipate the design features and data that will have to be acquired.

2.2 Task 2. Acquisition of Engineering Data and Drawings

2.2.1 As-Built Drawings

The as-built drawings may be located in variety of places. Unfortunately, as of date, there is no central repository for pump station as-built drawings. The storage location and format will depend on the age, purpose and initial ownership of the plant. For example, as-built drawings for relatively new pump stations constructed through the former Acceler8 program will typically be stored in electronic format by the District's Map File Room. On the other hand, as-built drawings for older pump stations may exist only in hard copy and be stored at an off-site location. When attempting to locate as-built drawings, past experiences of OHDM engineers with numerous rating analyses suggest that the following sources be considered in the order listed:

1. *The Map File Room.* Numerous as-built drawings are cataloged and stored here in either electronic or hard copy format. When contacting their staff for assistance, it is helpful to first determine the contract or project (CERP, ACCELER8, ECP or other) number pertaining to the pump station under consideration.

2. *O&M Engineering Department or ERRA.* Normally, these departments do not store as-built drawings on site. On some occasions, the project manager who oversaw construction of the pump station will have the construction drawings stored on a local CD. There is also the possibility that records for a relatively new facility can be accessed through Documentum. Typically, though, they are stored off-site and the storage box number will have to be determined. If the facility is not too old, one of the department's administrative assistants might be able to locate the box number in an electronic database. Otherwise, it will have to be located in their hard-copy records that are spread among several large binders (pump station constructed as part of the ECP are kept in a separate binder). One of the administrative assistants should be able to provide these. Unfortunately, this can prove to be a frustrating and tedious process.

3. *STA Management Division.* This organization may have electronic copies of the drawings or know the Documentum path to the pump station records if the pump station is a relatively new part of an STA.

4. *The pump station office.* The large, manned pump stations often store as-built drawings on site along with the station's O & M manuals. Contact the pump station office directly.

It is an unfortunate fact that as-built drawings for a pump station are often not available. If this is the case, the next best alternative is to obtain and use the construction drawings. A separate survey of the facility that adheres to the standards and objectives of the STRIVE project (Pathak and Chen, 2005) should then be initiated, if possible.

2.2.2 Material and Component Specifications

Certain specifications used in pump station construction need to be obtained. These are generally needed to accurately compute hydraulic energy losses within the station piping and appurtenances. Specifications for the following components should be obtained:

1. *Discharge conduit*. In particular, specifications related to conduit materials, inner linings and wall thicknesses are needed.

2. *Valves and appurtenances*. Obtain specifications for valves, elbows and other appurtenances where significant energy losses may occur.

3. *Engines and pumps*. Certain fundamental properties and specifications (design speed, engine type, etc.) are useful for understanding characteristics and operational protocol of the pump station. The design engine and pumps speeds, in particular, need to be determined. The *Structure Information Site* on the IWEB and the OHDM publication entitled, "Atlas of Flow Computations at District Hydraulic Structures" are sometimes useful sources of such information.

2.2.3 Pump Performance and Model Test Results

For each pump within the station, the pump performance curve or the relationship between Total Dynamic Head (TDH) and flow rate is normally required for rating analysis. For centrifugal pumps, this curve usually appears parabolic and concaves downward. Figure 2 shows an example of some performance curves provided by a pump manufacturer. The TDH vs. Q curves are shown in heavy black and, as expected, vary with pump speed. They are normally determined for a given pump model through standard test procedures in a laboratory setting. They should be included in the project records within a pump station design report, a hydraulic model test report or the station's O & M manual.

For very large pumps, the District usually requires that the manufacturer conduct hydraulic model tests of a model pump to determine the performance curves for the actual prototype to be installed. These tests are typically witnessed by a District engineer and the results are usually documented and stored with other project records. The test reports, however, usually contain other useful information besides the pump performance curves. The District sometimes requires the pump manufacturer to also determine energy losses within the intake and discharge works. These results are normally more accurate than the energy losses determined through desk top calculations as described in a latter section. Hence, they should be acquired if available.

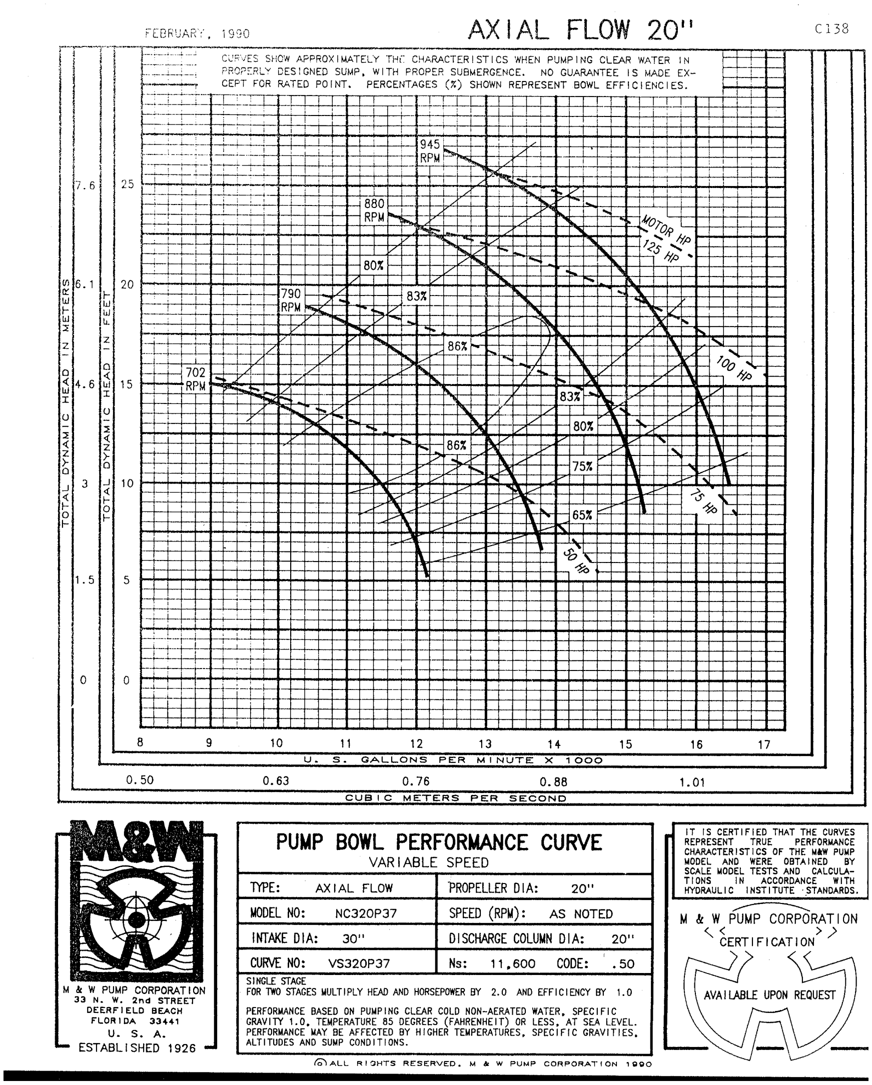

Figure 2. An example set of pump performance curves

2.2.4 Flow Measurements

Stream flow measurements that are useful for rating purposes should be available in the QMEAS database. However, there are exceptions. Flow measurement records are sometimes stored electronically in project folders without the results ever being stored in the database. Hence, it may be a good idea to review the folders stored under the following server directories:

\\Dataserv\570\5730\5733\Projects\QAQC of QMEAS data (ST060588-ECT)\Field Notes

\\Dataserv\570\5730\5733\Streamgauging\Measurements

If flow measurements not located in the database are found here, it is best to contact the stream gauging analyst who performed or supervised the measurement to determine if the measurement has been properly reviewed and to initially evaluate its potential use for rating analysis purposes.

2.2.5 Operation Manuals

The operation manual for the pump station can sometimes be found in either the same location as the as-built drawings or in the operations control room. Most of the time, it must be obtained directly from the pump station or associated field station. While much of the information contained in this manual may not be essential for conducting a rating analysis, it can be helpful in identifying the ranges of operation where the rating should be most accurate.

2.2.6 Repair and Maintenance Records

Pump stations sometimes undergo modifications that can affect the rating of an individual pump. For example, a pump originally specified may have been replaced or modified. If it is suspected that the pump station may have undergone such modifications, it is probably best to contact the field station in whose jurisdiction the pump station is located.

2.2.7 STRIVE Database

It is an established fact that as-built drawings can contain errors in dimensions and elevations. The STRIVE effort (Pathak and Chen, 2005) was carried out to partially rectify this problem. The resultant database contains resurveyed elevations for a number of pump stations. Hence, after acquiring the as-built or construction drawings, it is best that the pertinent elevations be verified against those in the database, if available. As of date, the STRIVE project results are located at \\dataserv\460\4620\4621\Strive.

2.3 Task 3. Evaluation of Engineering Data and Pump Station Properties

Once the information discussed in section 2.2 has been acquired and assembled, the tasks listed below should be performed.

2.3.1 Obtain Dimensions of the Intake Works

Many of the larger pump stations are designed with a special intake structure known as a Formed Suction Intake (FSI). This is a special type of hydraulic design whose purpose is to minimize turbulence, local eddies and vortices near the pump intake. If such an intake feature exists, then, at a minimum, the discharge diameter needs to be known in order to estimate energy losses through this substructure. It is advisable to acquire all the relevant dimensions, such as intake dimensions, splitter wall thickness and radius of curvature.

Most small to medium-sized pump units are fabricated with an intake bell, followed by a conduit that encases the pump bowl (Figure 1). The latter is typically referred to as the pump casing and has a diameter that is slightly larger than the pump impeller. The dimensions of each of these should be obtained from the as-built drawings or pump specifications.

2.3.2 Determine the Inner Diameter of the Discharge Conduit

Review the plans and specifications to obtain the inner diameter of the pump discharge conduit. Note that this is often not the same as the nominal diameter used to identify the pipe size. For unlined steel pipes with nominal diameters less than or equal to 12 inches, the nominal diameter is the same as the actual internal diameter. For larger sizes, the nominal diameter represents the outer diameter. In the latter case, one would have to obtain the pipe wall thickness from the specifications. If this information is not available, the specifications provided by Jones et al (2006) should be used.

It should also be determined whether or not the inside of the conduit is lined with cement mortar, plastic or other substance. Usually, large-diameter steel discharge pipes are not lined while smaller diameter station piping made of ductile iron is lined. The specifications should indicate the thickness of and material used for any linings. If a thickness is not specified, note whether or not the lining is installed on site or back at the manufacturing plant since this can affect the thickness. Jones et al (2006) provide useful information and data on pipe linings.

Many of the large pump stations have discharge conduits that are of a special geometric design that is intended to minimize local turbulence and energy losses. This type of design often includes bends, diffusers and splitter walls. The dimensions of these components will be needed to compute energy losses.

2.3.3 Estimate the Range of Hydraulic Roughness for the Discharge Conduit

The hydraulic roughness of the pump casing and discharge conduit is needed to compute energy losses as described in a latter section. This is usually specified in terms of absolute roughness (ε) given in units of length or in terms of relative roughness (ε/D; i.e., the ratio of absolute roughness to inner pipe diameter). The value of absolute roughness for a given pipe material can be obtained from Jones et al (2006), The Hydraulic Institute Engineering Data Book (1990), Wallingford and Barr (2006), or literature from pipe manufacturers. A range of roughness values is needed to account for variations in both manufactured pipe and field conditions.

2.3.4 Estimate the Ranges of the Local Head Loss Coefficients for Appurtenances

The range of local head loss coefficient K should be estimated for the pump inlet and each elbow, valve, diffuser and other appurtenance installed within the system. For a given appurtenance, this range can vary depending on the nature of its construction. For example, the energy loss incurred by flow through a swing check valve or elbow depends on whether its end connections are screwed or flanged. Jones et al (2006), the Hydraulic Institute Engineering Data Book (1990) and Mays (2005) provide useful data on local head loss coefficients.

In the case of a FSI structure, a local head loss coefficient for the entire intake structure is usually determined through physical model tests. If neither physical nor numerical model tests were specifically performed for the FSI structure under consideration, the next best alternative is to locate a geometrically similar FSI that was modeled and use the local head loss coefficient determined for it.

2.3.5 Review the Pump Performance Test Reports

The pump performance test report, if available, should be reviewed to determine the relationship between TDH and flow rate (i.e. the pump performance curve) at design speed for each type of pump within the pump station. Such a report normally provides the test procedure along with sample calculations used to determine this relationship from the test results. In reviewing the test results, it is usually a good idea to repeat some of the calculations to ensure that the correct results have been identified. In addition, it should be noted that sometimes the hydraulic model tests also produce the relationship between TSH versus flow rate (i.e. the pump unit performance curve) at design speed. In the latter case, the test procedure also evaluated the energy losses through the intake and discharge works. It is important that one relationship not be mistaken for the other.

2.3.6 Review the Flow Measurement Data

Each candidate measurement should be subject to a rigorous technical review that reveals the reliability and uncertainty of the measurement. Many flow measurements have been reviewed in such a manner through a quality control process developed by ECT and Sutron Corporation (2008). It is highly recommended that all flow measurements considered for use in the rating analysis be reviewed accordingly.

There are essentially two goals of the flow measurement review process, namely (i) to estimate the uncertainty of each measurement, and (ii) to categorize the potential use of each measurement in the rating process. More specifically, measurements should be categorized as follows, in order of decreasing quality:

1. Measurements that the rating equation can be directly fit to through regression;

2. Measurements that the pump station performance curve (described below) can be calibrated to;

3. Measurements that the pump station performance curve can be validated against;

4. Measurements that can provide a "soft check" of the pump unit performance curve – that is, it is known that the curve should produce a discharge rate that is either greater than or less than the value of the measurement;

5. Measurements that should not be used at all in the rating analysis.

2.4 Task 4. Determine the Pump Unit Performance Relationship

The goal of this task is to use the engineering properties of the pump station to determine, for each pump, the relationship between the total static head across the pump station and the pump unit discharge rate at design speed. This is accomplished by performing the subtasks given below in the order listed.

2.4.1 Compute the Head Losses Associated with Various Discharge Rates

For each pump, the discharge rates used to determine its performance curve should be used to compute the head losses associated with those discharge rates. This includes all local and friction head losses in the system between the head water and tail water monitoring stations. Friction head losses should always be computed using the Darcy-Weisbach equation. It can be stated as:

$$S_f = (f/D)\, V^2/2g \quad \text{……………………………………….} (1)$$

where S_f is the friction head loss per unit foot, D is the pipe diameter, V is the mean flow velocity and f is the friction factor. A comprehensive discussion of this equation is provided by Daugherty and Franzini (1977). In the past, energy losses due to friction have often been estimated with the Hazen-Williams formula. However, an investigation by Bombardelli and Garcia (2004) indicates that this formula has a limited range of application and is not as accurate or reliable as conventionally assumed. In particular, it is only applicable within the transition or smooth, turbulent flow regimes. Furthermore, Daugherty and Franzini (1977) indicate that the flow velocity must be less than 10 ft/s. The various limitations of this equation have been demonstrated by other investigators as well, including Diskin (1960) and Liou (1998), who recommended that it not be used in engineering practice.

Despite these concerns regarding the reliability of the Hazen-Williams formula, it has found a longstanding acceptance in engineering design since any inaccuracies inherent to it may be off set by selecting a conservative value for the coefficient C. In contrast, when analyzing an existing facility for the purpose of estimating discharges as accurately as possible, the engineer does not have this convenient fallback. Consequently, to enhance the reliability of flow estimates while avoiding needless errors in hydraulic head loss calculations, it is recommended that the Hazen-Williams formula not be used in conducting hydraulic rating analyses of the District's pumping stations.

In the transition range between smooth and rough-pipe turbulent flow, Swamee and Jain (1976) proposed the following convenient expression for Darcy-Weisbach friction factor:

$$f = \frac{1}{4\left[\mathrm{Log}_{10}\left(\varepsilon/(3.7D) + 5.74/N_R^{0.9}\right)\right]^2} \quad \text{…………………………………}(2)$$

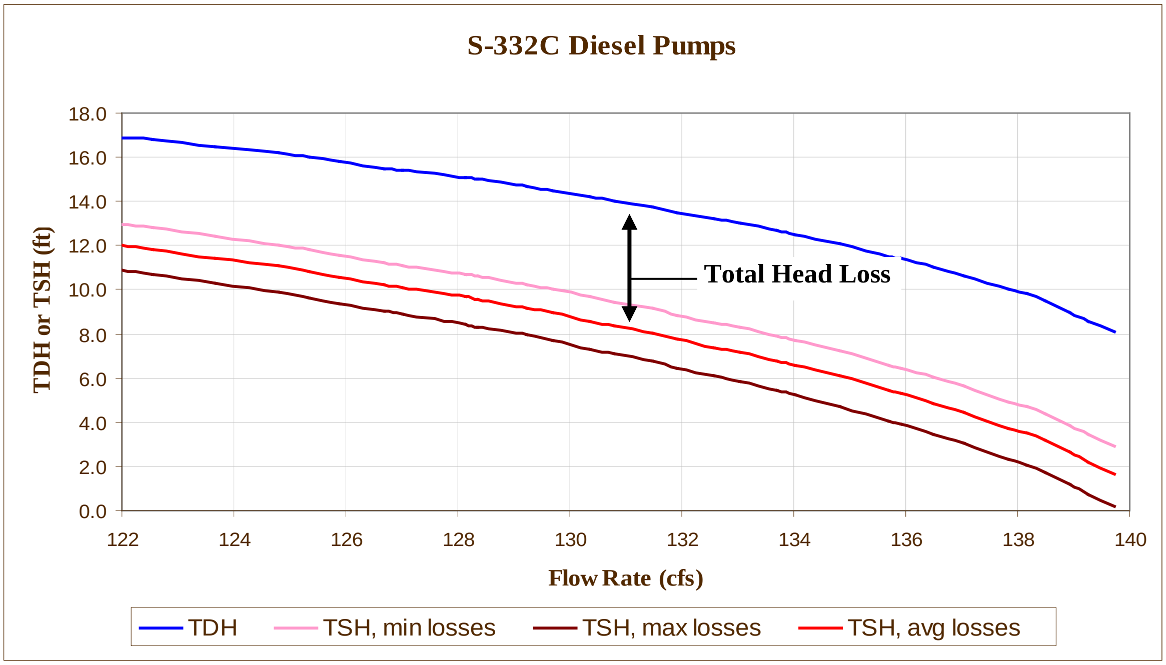

Figure 3. A pump unit performance curve for S-332C

Friction factors computed with Equation 2 can be checked against those obtained with a Moody diagram. Equations 1 and 2 can be used along with the pipe length to compute the total friction loss within the discharge pipe. This should be done for both the minimum and maximum values of pipe wall roughness. The associated minimum and maximum f values can be averaged to compute the average friction losses.

Similarly, the minimum, average and maximum values of the total local head loss associated with each elected flow rate should be computed using the ranges of local head loss coefficients determined previously. The total local head losses should be added to the total friction head losses to obtain the total head loss associated with each flow rate.

2.4.2 Construct the TSH versus Q Relationship for Each Pump

The results of 2.4.1 can be used to construct the pump station performance curve for each pump unit. An example of this is shown in Figure 3 for the pump station S-332C diesel pumps. Note the estimated uncertainty range due to the uncertainties in pipe roughness and local head loss coefficients. The pump unit rating will be based on the pump unit performance curve reflecting average head losses.

2.4.3 Compare the TSH versus Q Relationship(s) to Measured Flow Data

At this point in the analysis, the pump station performance curve for each pump unit should be compared to the associated measured flows that have been reviewed as outlined in section 2.3.5. The values of the pipe roughness and local loss coefficients can be adjusted within their established ranges to improve agreement while giving greater preference to the higher quality data. An example of this type of comparison for pump station G-335 is shown in Figure 4. In this case, no adjustment of computed head losses was needed. If reasonable agreement cannot be attained, further investigation of the measured flow data, the pump performance data and/or pump station properties may be warranted.

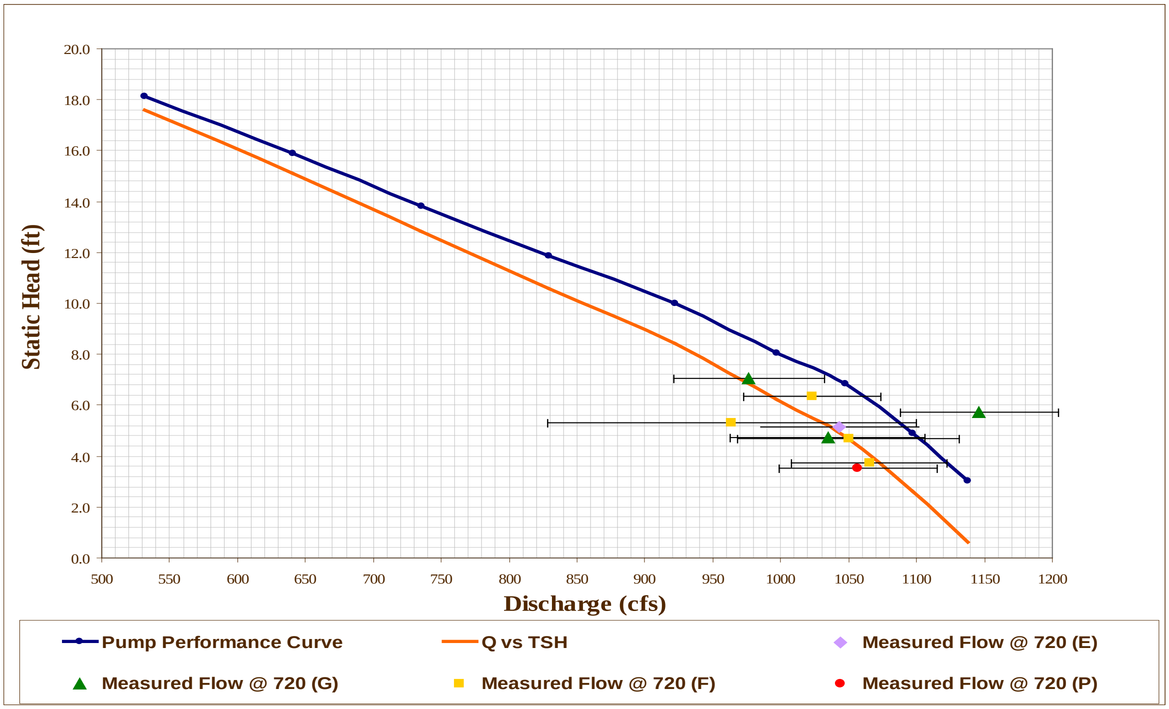

Figure 4. A pump unit performance curve for G-335 compared to measured flows

2.5 Task 5. Determine the Rating Equation Parameters

The final step in developing the rating equation is to fit the rating model to the outcome of task 4. This model can be stated as (Imru and Wang, 2003)

$$Q = A\left(\frac{N}{No}\right) + BH^{C}\left(\frac{No}{N}\right)^{2C-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where Q is the discharge rate, N_O is the design pump or engine speed, N is the actual pump or engine speed, H is the total static head across the structure, and A, B and C are parameters to be determined through curve fitting. For pumps driven by electric motors, $N = N_O$ in almost all cases. Hence for electric-powered pump units, Equation 3 reduces to $Q = A + BH^C$.

Equation 3 is normally fit to each pump unit performance curve developed in the previous step. However, there are exceptions to this. If, for example, adequate flow data exist while the manufacturer's pump performance curve is not available or is no longer considered reliable, Equation 3 would be fit directly to the measured flow data (see, for example, Wilsnack, 2007). In either case, nonlinear regression techniques are typically used to perform the curve fitting (a SAS script has been developed for this purpose). The resultant rating equation should be compared to the pump unit performance curve to verify agreement. Any deviations between the two should be negligible throughout the expected operating range of the pump.

2.6 Task 6. Perform an Impact Analysis

An impact analysis is performed to evaluate need to recompute historical flows with the new rating equation. If the pump is new or recently modified, then the new rating equation would obviously not apply to the historical period of record (if one exists) and no impact analysis would be necessary. Otherwise, the period of record over which the new rating equation is applicable should be identified (the results of subtask 2.2.5 may be useful here). In many cases, it is simply the entire life of the pump station.

The next step is to locate all of the static data in the *production* version of the HydroEdit database that pertain to the pump in question. These should match the corresponding data fields in the *development* version of the HydroEdit database. If not, change the data values in the development database so that they match those of the production database. Examples of relevant data fields include discharge pipe diameter, flap loss coefficient, etc.

At this point, the parameters of the new rating equation should be entered into the appropriate fields of the development database. These fields are located on the Case 8 tab of the pump properties form.

The final step is to use the new rating equation to recompute the break point flows over the established period of record. This involves running the *production* version of the FLOW program while reading all static data and parameters from the development version of the HydroEdit database. A set of scripts that performs this task is available. The output from these scripts can be converted to mean daily flows using the *runivg* program. This set of mean daily flows should be compared to the corresponding set of flows currently in DBHYDRO. This comparison should be made in accordance with the standard operating procedures for DBHYDRO flow data management.

2.7 Task 7. Documentation

The final task is to document the results of tasks 1 – 6. The scope and extent of the documentation will vary depending on the size, function and complexity of the pump station. For example, the rating analysis for a small, seepage return pump station of simple design can be adequately documented in a Technical Note. In contrast, a large STA inflow pump station with an unusual design should have its rating analysis documented in a SHDM Technical Publication. Moreover, an intermediate facility should have its rating analysis documented on an OHDM Technical Bulletin. At the current time, however, there are no hard and fast policies dictating what the documentation scope and format should be for a given pump station. In any case, though, each type of document has a standard template and review procedure that should be adhered to when preparing the report.

3.0 SUMMARY

The rating analysis procedures and tasks outlined above are intended to provide general guidance and direction in conducting rating analyses of District pump stations. They cannot (nor are they intended to) address all issues and situations that may arise in any given rating analysis. One must bear in mind that sound engineering judgment, experience, and familiarity with the pump station under consideration are essential for developing a defendable and accurate rating equation.

4.0 FUTURE EFFORTS

It should be noted that the rating procedure, at this time, only offers relatively simplistic guidance for assessing the uncertainty of the pump unit performance curves that the rating equations are intended to model. In particular, the uncertainty of computed flows hinges solely on the uncertainties in the computed head losses. It's possible that a more comprehensive approach to addressing the uncertainties inherent to computed flows can be formulated though the use of inverse parameter estimation techniques or Monte Carlo based methods. This is currently under investigation.

5.0 REFERENCES

Bombardelli, F. A. and M. H. Garcia. 2003. "Hydraulic Design of Large Diameter Pipes." *Journal of Hydraulic Engineering, ASCE*, 129(11), 839-846.

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

Diskin, M. H. 1960. "The limits of applicability of the Hazen-Williams formula." *Houille Blanche,6,* 720-723.

ECT and Sutron Corporation. 2008. Quality Assurance of Field Flow Measurements at SFWMD Structures. Deliverable 7.0, Contract No. ST060588-WO01, 50 pp.

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

Jones, G. M., B. E. Bosserman, R. L. Sanks and G. Tchobanoglous. 2006. *Pumping Station Design*. Butterworth Publishers, Stoneham, MA.

Liou, C. P. 1998. "Limitations and proper use of the Hazen-Williams equation." *Journal of Hydraulic Engineering, ASCE*, 124(9), 951-954.

Mays, Larry W. 2005. *Water Resources Engineering.* John Wiley & Sons, Inc., Hoboken, NJ.

Pathak, C. and M. J. Chen. 2005. Evaluating and Improving Flow Data Quality Using STRIVE Data at Water Control Structures. Volume One, Technical Publication ERA # 428, Operations and Hydro Data Management Division, South Florida Water Management District, West Palm Beach, Florida, 30 pp.

Swamee, P. K. and A. K. Jain. 1976. "Explicit equations for pipe flow problems." *Journal of the Hydraulics Division, ASCE*, 102(5), 657-664.

Wallingford, H. R. and D. I. H. Barr. 2006. *Tables for the hydraulic design of pipes, sewers and channels*. Thomas Telford, London, England.

Wilsnack, M. 2007. Flow Rating Analysis for Pump Station S-331. Technical Publication ERA # 456, South Florida Water Management District, West Palm Beach, Florida, 34 pp.