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Hydrometric Manual – Data Computations

Stage-Discharge Model Development and Maintenance

Water Survey of Canada
Environment and Climate Change Canada
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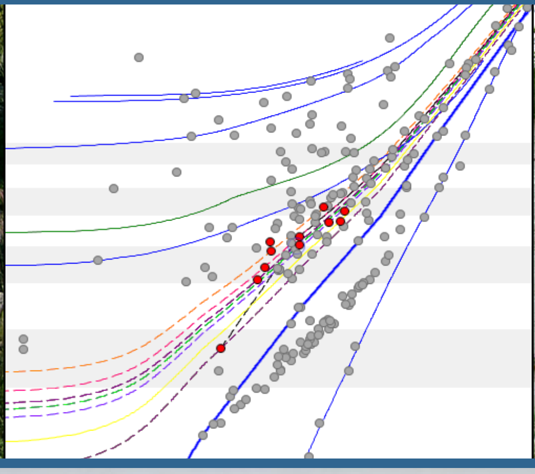

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Version aussi disponible en français.

Front Cover: Left, Roy Penner surveying a dry bed. Right, Curtis Smith at Highwood River during a flood.

Back Cover: Left, Sage Creek hydrometric station. Right, water survey engineers around 1908.

Revision History

Version. No.	Date	Source	Description/Rational for Change
0	2012-12-17	OMC-H / NetOps / DCS	Beta Version
1	2016-04-14	National	Version 1 of previous Data Computations chapter now organized as specific document.

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Terminology

Approval Period	Dates over which a period of data is raised from Provisional to Final.
Approved Data	Data that is the best produced with information available and adopted standards and procedures. It is synonymous with final data.
Backwater	The increased depth of water upstream from an obstruction in a stream channel due to the existence of such obstruction, and the raising by it of the water level a considerable distance upstream.
Bankfull stage	Stage at which an open watercourse just overflows its natural banks.
Check Measurement	An additional discharge measurement obtained during a site visit to confirm a discharge measurement that deviates from the expected value.
Computation Lead	Person responsible to compute data at any given station.
Continuous Data Production	Process where data evolves on a time scale that is as close to the last station visit as possible.
Control	The sum of the features located downstream of the gauge which influence flow and govern the stage-discharge relation.
Hydrograph	Relation in graphical form between time and flow variables such as discharge and stage.
Hysteresis	Phenomenon where the relation between stage and discharge is not uniquely defined without additional parameters such as water surface slope or rate of change in flow
Offset	Number subtracted from all stage values in a stage-discharge relation so that measurements and the equation plot as a straight line in logarithmic space.
Peer Review	Process under which hydrometric data is reviewed by another technologist for compliance with standards and procedures.
Provisional	Publication status describing best available but still evolving data.
Publication	Any means, temporary or permanent, by which data are made available to clients and users.
Real-time Data	Preliminary data flowing from the station to the web publication services as soon as it has been received by telemetry and been subjected to automated corrections and models. It is the best available representation of a station current condition.
Segment	Region of a stage-discharge relation governed by a unique control which corresponds to a specific hydraulic equation.
Station Analysis	Description of decisions made during data computation which explain how records were produced.
Transition	Region of stage-discharge relation governed by more than one type of control and which does not follow any specific hydraulic equation. It is synonymous with compound control.

Foreword

Water Survey of Canada is the federal agency responsible for the collection, interpretation and dissemination of standardized hydrometric data and information in Canada. It is a well-respected organization, proud of its traditions and accomplishments spanning over 100 years but also progressive in its attitudes. The Water Survey of Canada is an ISO 9001 certified organization committed to the principle of continuous improvement.

Adopting standard practices for rating curve development and maintenance is essential to our mandate. This document was built on the best references available and in close consultation with theoretical as well as operational experts, within Water Survey of Canada and worldwide. These standard operating procedures describe techniques that should enable our employees to consistently produce good data, based on sound science and our operational reality.

Many of our employees and collaborators from other agencies, universities and private enterprises offered support which enabled the development of this document. We thank everyone for their effort in contributing to these procedures and are confident that it will help maintain our reputation of excellence for years to come.

Al Pietroniro
Director, National Hydrological Services
March 2016

1 Stage-Discharge Model Development and Maintenance

Rating curves are relations used to model discharge as a function of one or more variables. The purpose of this document is to guide technologists through the development and maintenance of simple stage-discharge models. Techniques required to develop complex ratings are not covered, but criteria to identify such cases are included.

1.1 Basic Concepts

Familiarity with the basic concepts of open-channel flow is essential to develop stage-discharge rating curves. The development of stage-discharge ratings requires informed judgment to interpolate between measurements and extrapolate beyond their range.[1] The *Computation Lead* must have received sufficient training, which typically corresponds to the completion of relevant lesson plans in the Apprenticeship or Professional Training Program.

1.1.1 Simplified Hydraulic Equation

WSC procedures assume that stage-discharge ratings can be based on Manning's simplified hydraulic equation defined in this section. <u>The simplified hydraulic equation assumes open-water, steady, uniform flow.</u> When the application of this equation is possible, it offers a higher level of confidence in data produced because there is less variation and interpretation in how the curve can be constructed. The relation is usually apparent and easily modeled. Simple ratings may consist of several segments generally defining low, medium, and high (overbank) *control* ranges connected by short *transitions*.[2]

In most cases, care invested while selecting a gauging site allows the use of the simplified hydraulic equation assumption, but this must be regularly assessed. Such simple modeling conditions apply sufficiently well to about 75% of WSC sites.[3] Criteria listed in section 1.1.2

[1] WMO No. 1044, Volume 2, page 1.1
[2] Kennedy 1984
[3] Environment Canada 2015

Detecting Complex Conditions may help to determine when such an assumption is clearly violated and additional resources are required to fit another model.

The simplified hydraulic equation can be expressed as:

$$Q = C(H - h_o)^b \tag{1-1}$$

- $\boldsymbol{Q}$ is the discharge.
- $\boldsymbol{H}$-$\boldsymbol{h_o}$ is the effective depth of water (hydraulic head) above the *control*, where $\boldsymbol{H}$ is the gauge height relative to the station datum and $\boldsymbol{h_o}$ is the gauge height of zero flow, also called the *offset*.
- $\boldsymbol{C}$ is the calibration parameter influenced by width, slope, bed roughness and other channel characteristics.
- $\boldsymbol{b}$ is the calibration parameter influenced by the *control* geometry, known as the rating exponent when the relation is displayed in logarithmic scale.

The simplified hydraulic equation takes the form of a linear equation if the logarithm is applied to both sides. On a log-log graph, the exponent $\boldsymbol{b}$ is the slope and *log(C)* is the intercept.

$$\log(Q) = \log(C) + b\log(H - h_o) \tag{1-2}$$

1.1.2 Detecting Complex Conditions

About 25% of WSC sites correspond to complex rating conditions.[4] Complex ratings are those predominantly described as:

- non-linear (in log-log space), as they cannot be modeled using Manning's simplified hydraulic equation;
- non-unique, when multiple discharge values can occur at a given stage value; or
- highly unstable, because the frequency of field visits is insufficient to characterize the rapidly evolving relation.

Conditions at a site may have evolved since a rating was created, causing the simple approach to fail. Measurements obtained at complex sites may contain variations not well understood or difficult to account for during the construction of a rating. The effects of different hydraulic conditions on ratings can be observed in Figure 1.

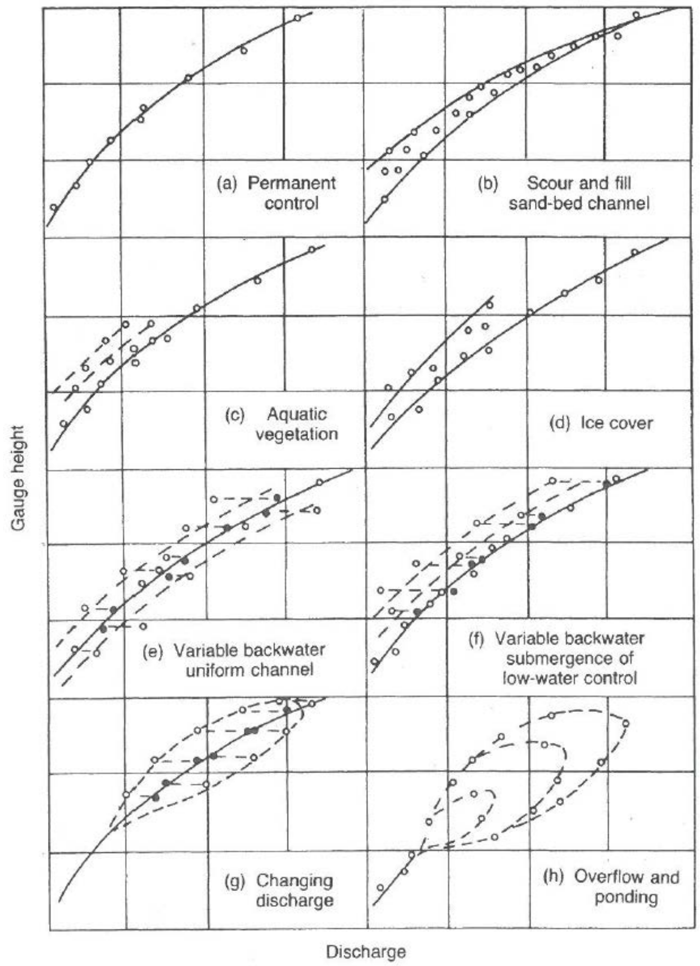

Figure 1. Effects of different hydraulic conditions on ratings displayed in rectilinear coordinates (from: Herschy 1995)

Complex rating conditions must be identified because complex rating development requires a greater level of expertise than is commonly available and a different modeling approach than the one promoted in WSC general procedures. The *Computation Lead* must assess monitoring results to detect any major departure from the simple rating assumptions. If any of the following questions is answered positively, the *Computation Lead* must report the information to their supervisor and determine if an alternative modeling approach should be considered:

[4] Environment Canada 2015

1. Is the *control* affected by variable *backwater*?
    - Variable *backwater* is a phenomenon where the flow is obstructed downstream, causing water levels to rise independently of the discharge. Sources of variable *backwater* are downstream reservoirs, tributaries, tides, dams or other obstruction that may influence the flow at the gauging-station *control* (See Figure 1-e and f). Variable *backwater* is not the same as seasonal influences such as vegetation or ice (See Figure 1-c and d).

2. Are there signs of *hysteresis* during episodes of rapidly rising and falling water levels?
    - Hysteresis (loop rating) is a phenomenon where the relation between stage and discharge is not uniquely defined without additional parameters such as water surface slope or rate of change in flow (See Figure 1-g). It can exist at all locations, but is most pronounced in relatively flat-sloped rivers. When stage changes rapidly, the water surface slope is different than in steady-flow conditions, resulting in flow acceleration or deceleration which makes the simple rating assumptions invalid.[5]

3. Does the flow frequently go over the banks?
    - Over-bank flow is affected by complex interactions between the main channel and flood plains (Overflow and ponding. See Figure 1-h). Such interactions are difficult to represent with a simple rating equation.[6] In addition, the upper end of a rating may not adequately define discharge in the flood plains simply because a small change in stage creates a large change in discharge.

4. Are the calibration measurements regularly more than 5% off the predicted values?
    - The rating may produce little prediction accuracy (See section 1.1.6 Rating Stability).[7]

5. Is it difficult to fit an equation against field observations?
    - Patterns and biases may be visible in the residual plots, suggesting that other variables influence the stage-discharge relation (See section 1.2.6 Calibrating the Rating Equation).

1.1.3 Stage-Discharge Controls

Stage-discharge ratings are governed by features located downstream of the gauge which influence flow. The sum of those features is thus called a control. Controls can be naturally occurring or constructed for the purpose of hydrometric monitoring.

Lower flows are usually governed by "*section controls*" whereas higher flows are governed by "*channel controls*". Mid-range flows may be influenced by a combination or compound control. Higher flows may be subjected to different physical laws than what the simplified hydraulic equation describes if they spread over banks and into the "*flood plains*".

1.1.3.1 Section Controls

Section controls are features such as a rock ledge, a sand bar, a severe constriction in the channel or an accumulation of debris. If man-made, section controls can be a small dam, a weir, a flume, or an overflow spillway. Section controls are identified by observing a riffle, or pronounced drop in the water surface, as the flow passes over the control. Frequently, as stage increases with higher flows, the section control will become submerged and will no longer govern the relation.[8]

1.1.3.2 Channel Controls

Channel controls consist of a combination of features spread throughout a reach downstream from a gauge. These features include channel size, shape, curvature, slope and bed roughness. The length of a channel

[5] WMO 1044, Vol 2, p.1-3
[6] ISO 1100-2, p.5
[7] Pyle 1999, p. 29
[8] WMO 1044, Vol 2, p.1.2

control varies depending on how steep or flat the channel is, as well as the magnitude of flow. Knowing the length of a channel control reach is usually neither possible nor necessary.[9]

1.1.3.3 Compound Controls

The relation between stage and discharge may sometimes be governed by more than one type of control. This usually occurs for a short range in stage between different control features and is referred to as a *transition*. *Transitions* do not follow any specific hydraulic equation per se. They are empirically defined.

1.1.3.4 Artificial Controls

Either section controls or channel controls can be artificial controls. Artificial controls are man-made. They provide great advantages for the development and extension of ratings because the equation describing an artificial control (e.g. weir) can be directly entered into the data computation system as basis for a rating at such sites. Ratings may also be accurately and efficiently extended based on man-made control information as long as the flow is within the structure limits.

1.1.3.5 Flood Plains

Flood plain controls are influenced by features similar to those in channel controls. However, flow events of such magnitudes are likely to change all but the most stable control features. In addition, at such levels, discharge is likely to depend on more than stage with the increased possibility of large overbank storage, the increased influence of variable *backwater* or rapidly changing discharge causing *hysteresis*. This will then limit the use of a simple model.[10] [11]

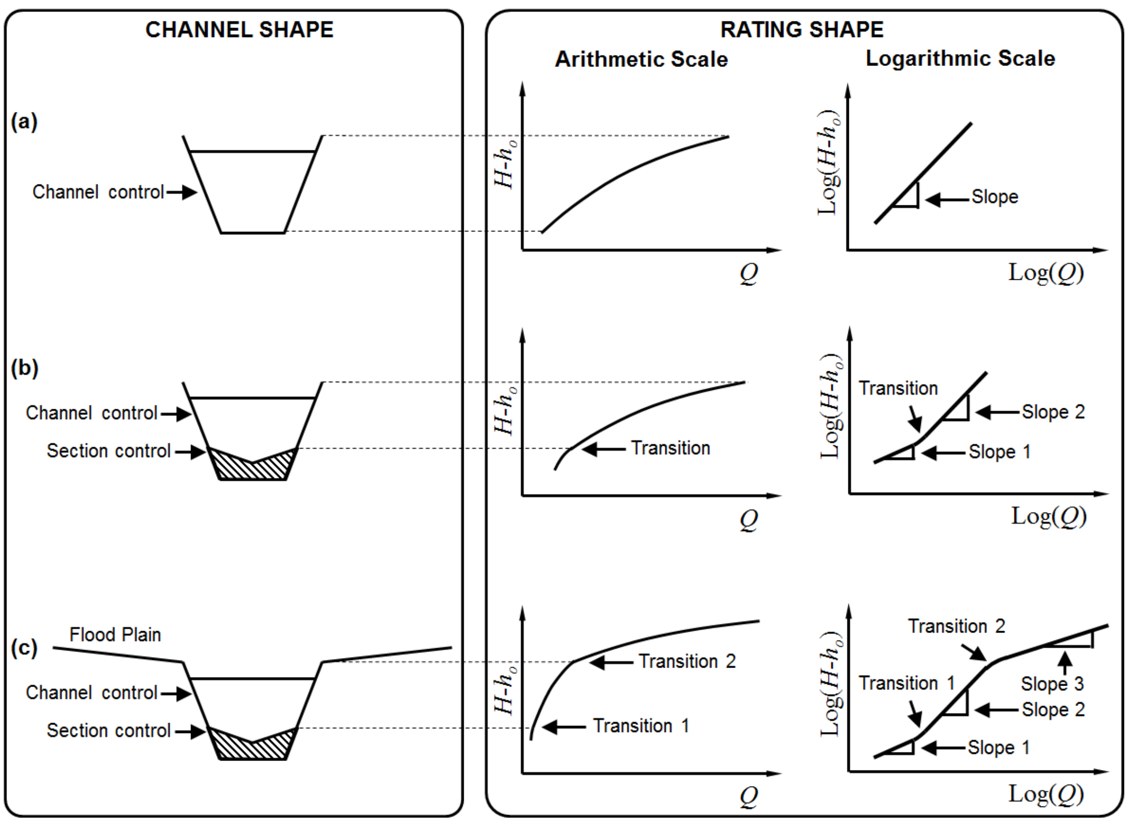

Figure 2. Relation between control properties and rating shape: (a) Trapezoidal channel control with no flood-plain. The rating is a single line over the full range of stage. (b) Section control and trapezoidal channel control. The rating changes when the water level is above the height of the section control. (c) Section control and trapezoidal and flood plain channel controls. The rating has 3 segments and 2 *transitions*. (Adapted from: WMO No.1044, Vol 2)

[9] WMO 1044, Vol 2, p.1.2
[10] Boiten 2008
[11] Herschy 2009, p.159

1.1.4 Rating Exponents

The rating exponent b is influenced by the shape of the channel cross-section. The exponent is important during the preliminary development of a new rating.[12] The value obtained during calibration should be related to plausible results (See Table 1).

Table 1. Rating exponent, *b*, values to expect for a specific control geometry

Shape	General Range for exponent b
Triangular	2.5 to 3.0
Parabolic	1.7 to 2.3
Rectangular	1.3 to 1.8

For relatively deep narrow rivers with section control, the rating exponent will likely be greater than 2 and may even exceed a value of 3.[13] For relatively wide rivers with channel control, the rating exponent will generally vary between 1.3 and 1.8.

As stage increases, controls are drowned and new ones are successively introduced. When stage goes over the banks, many new factors start to influence the relation, but mainly the overall cross-section starts to increase rapidly, so that for any increment in water level, the rise in discharge is much bigger than at lower water levels. This typically translates into a larger rating exponent relative to lower controls and causes a straightening out of the rating parabolic curvature when displayed in rectilinear coordinates.[14]

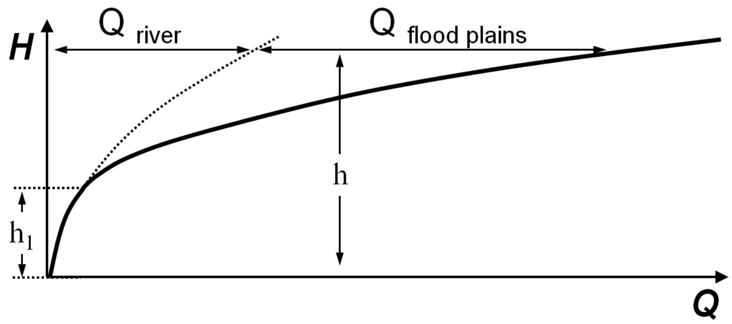

Figure 3. Rating curve in linear space for river with flood plains (from: Boiten 2008)

Calibrated values may often deviate from those suggested above in Table 1. Channel shapes are rarely regular and symmetrical, making it difficult to determine which geometry may actually represent surveyed conditions. In addition, the effect of velocity or pressure head at the control may contribute to a significantly higher calibrated exponent than based on geometry alone.

1.1.5 Offset

The variable h_o in the simplified hydraulic equation is called the *offset*. It corresponds to the gauge height of zero flow for section controls. For channel controls, the term $H\text{-}h_0$ corresponds to the hydraulic radius. The *offset* must be adjusted so that all measurements related to any specific equation plot on a straight line. Only one scale *offset* will cause a rating segment to plot as a straight line on any logarithmic scale plot.[15] Note that *offsets* are not always the same for all segments included in a rating.[16]

Offset values associated with section controls should relate to the lowest point at which flow can be observed. For other controls higher up in the rating range, *offsets* represent a mathematical concept that does not relate to any physical property of the control, so there often exists no feature corresponding to the *offset* defined for a channel control.

[12] Herschy 2009, p.168
[13] Herschy 2009, p.168
[14] Herschy 2009, p.159
[15] USGS 4044, p.40. Section 7.7.6.2
[16] Braca 2008

Offset values are usually positive and increase from the lower control segments to the higher ones, but the opposite is not impossible. Negative *offsets* are atypical as they would indicate that the gauge height of zero flow is below the station's assigned datum.[17]

1.1.6 Rating Stability

A stable rating is one that does not change permanently or significantly over time. Stable ratings are related to stable channels and section controls such as rock outcrops, and man-made structures such as weirs, flumes and small dams.[18] Complete stability is rare, as any channel can be permanently changed as a result of scour or deposition. At some locations, control characteristics such as geometry and friction properties vary continuously with time.[19] At highly unstable sites, it may be possible to apply the simplified hydraulic equation but it is then only possible to estimate the temporary position of the rating between available discharge measurements.[20] Note that unstable does not mean complex. A simple rating could have a rapidly shifting control.

[17] WMO 1044, Vol.2, p.6-25
[18] Braca 2008, p.9
[19] ISO 1100-2, p.11
[20] ISO 1100-2, p.11

1.2 Rating Development Strategy

The development of a rating is an ongoing process. It consists in systematic observations and measurements of site control characteristics. The information obtained is then used to formulate a hypothesis that will be tested, and possibly modified, based on future observations and measurements. The role of the *Computation Lead* is to define a model that will provide a good fit to empirical evidence and hydraulic assumptions for the site.

1.2.1 General Development Process

The development of a new rating or the review of an existing one is an iterative and deductive process that does not follow any strict sequential order. Nevertheless, the following 7 steps are recommended:

1. Formulating a model hypothesis.
2. Selecting and plotting relevant measurements.
3. Estimating the *offsets*.
4. Defining the applicable range for all equations.
5. Calibrating the rating equations.
6. Calibrating the *transitions*.
7. Identifying any estimated range.

Throughout each of these steps, it is essential to properly document any decision and detail. See section 1.4 Rating Metadata.

1.2.2 Formulating a Model Hypothesis

A clearly spelled out working hypothesis will help to efficiently develop the most robust rating model. The hypothesis will also guide future monitoring efforts which in turn will result in refined assumptions.

The *Computation lead* should first assume the simplest model suitable for all available site information. Using multiple controls is fine, but such complexity in the model structure should be justified. If too many control segments are used, random noise in data may influence the model design and increase uncertainty in discharge values calculated with this model.[21]

All available observations and hydraulic principles applicable to the site studied should be reviewed to identify:

- controls affecting flow patterns
    - number
    - type, describing likely sources of flow influence
    - expected range in stage,
- any range in stage where assumptions are ambiguous, which should be the focus of further investigation.

The *Computation lead* must clearly articulate such assumptions and document them in the *Station Analysis*. See section 1.4 Rating Metadata for details.

1.2.3 Selecting and Plotting Relevant Measurements

The Computation Lead must identify all measurements that should be considered during the development of a rating. This information must be documented so it is also available to future reviewers.

1.2.3.1 Measurement Selection

The Computation Lead must try to create a calibration sample that is bias free and representative of open water, steady and uniform flow conditions. With few measurements typically available (often less than 30), only

[21] NIST/SEMATECH 2012, Section 4.4.2.2

a substantial departure from a normally distributed sample will be detectable.[22] It must be understood that interpretation will therefore be essential while using the limited number of selected measurements to develop a rating.

Measurements are selected through the careful review of information collected in the Hydrometric Survey Notes and in the measurement details. Measurements should be selected if:

- They were obtained during open-water, steady, uniform flow conditions. Flow during these measurements is not expected to have been affected by shifting control conditions (conditions suspected to lead to a shift include debris, alterations by humans or animals, vegetation, fill, scour and ice.[23] See section 1.4.3.1 Control Conditions for details.)
- They were collected according to standard procedures. A *check measurement* should accompany any measurement that is sub-standard, atypical, or more than 5% away from rating predictions.[24] Note that measurements which deviate significantly from other results may only be omitted based on a rational and well justified argument, after consultation with the gauging party involved if possible.[25]
- They represent historical conditions rarely observed (e.g. high water).[26] However, they should be computed and expressed relative to the current datum. They should not include any bias caused by changes in technology or methodology. No change in river morphology (e.g. new bridge or landslide) should have impacted site conditions since their collection.[27]

All selected measurements must be identified in the Rating Metadata. See section 1.4 for details.

1.2.3.2 Sample Size

Sufficient information is required to justify the level of complexity assumed in any rating structure. As a general rule, the size of the measurement sample should be twice as large as the number of parameters that have to be calibrated in any rating. More specifically:

- For each rating segment, the parameters C, b and h_o (See section 1.1.1 Simplified Hydraulic Equation) should be calibrated using at least 6 measurements.
- Any *transition* between segments corresponds to a single parameter which should be defined using at least 2 measurements.

For example, and ideally, a rating where only one segment is expected would require 6 calibration measurements. Similarly, ratings with 2 segments would need 14 measurements (2 segments x 6 + 1 transition x 2) while ratings with 3 segments would require 22 measurements.

Note that the number of measurements used to establish a rating curve is not the only important factor during its calibration. The sample distribution and other site observations are as important as the number of measurements available. Measurements should be evenly spread over the entire range of the rating, ensuring that each segment and *transition* is defined by sufficient and significant information.

1.2.3.3 Graphical Representation

Plotting the selected measurements on a graph is often the first step towards the identification of basic rating characteristic. It helps assess if a simplified hydraulic equation can be fitted to the selected measurements.[28] In Water Survey of Canada, to facilitate interpretation, the independent variable of stage is plotted as the ordinate (Y-axis) and discharge as the abscissa (X-axis), which is opposite to standard engineering practice.[29]

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[22] Devore 2000, p.192
[23] Spehar 2013
[24] For details on check measurements, refer to Hydrometric Field Manual – Measurement of Streamflow.
[25] NEMS Steering Group 2016, Section 2.3.3.6
[26] Rantz 1982, p.344
[27] NEMS Steering Group 2016, Section 1.3
[28] NIST/SEMATECH 2012
[29] Sauer 2002, p.48

A rating can be represented in either logarithmic or arithmetic scales. Both scales have different benefits:

- Logarithmic scales help to combine theoretical expectations with empirical evidence.[30] As they allow rating equations to be displayed as straight lines, this makes their identification and calibration easier and usually more precise. Note, however, that rating equations appear linear only if the proper *offset* is applied. See section 1.2.4 Estimating the Offsets for details.
- Arithmetic scales are better suited to analyse ratings in their lower range, especially since logarithmic scales cannot be applied to zero or negative numbers. Arithmetic scales are also easier to read and relate to their field context. However, for detailed hydraulic analysis, arithmetic scales have little or no advantage over logarithmic scales since a rating plotted on a linear scale is almost always a curved line, concave downward, which can be difficult to shape correctly if only a few measurements are available.[31]

1.2.4 Estimating the Offsets

As stated above, the *offset* h_o must be properly adjusted in order to allow measurements related to a rating equation to plot against a straight line in logarithmic space. Only once the best suited *offset* has been identified can other parameters be calibrated for that segment. The two following methods are recommended to define h_o.

1.2.4.1 Trial and Error

For most controls, a good estimation of the *offset* can be obtained via trial and error. A value is obtained by defining the scale *offset* at which calibration measurements seem to follow a straight line when viewed in logarithmic scale. This method assumes a measurement sample that is a good representation of a specific control. All measurements used must belong to the same segment. The *offset*, which is subtracted from the stage value associated with each measurement, is increased or decreased until the data for a segment plots as a straight line.[32] If h_o is too low, the plot (H-h_o vs Q) will appear concave up (Figure 4 (a)). If h_o is too high, the plot (H-h_o vs Q) will appear concave down (Figure 4 (b)).

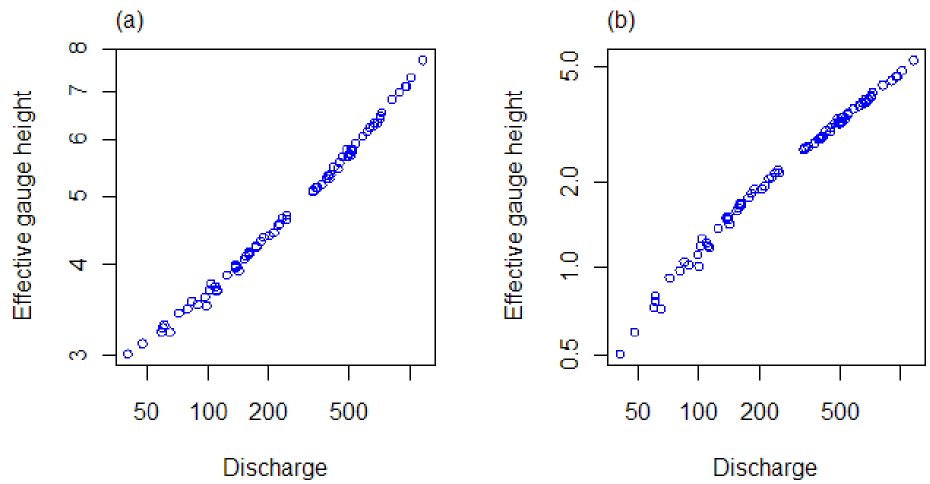


Figure 4. Adjusting the gauge height of zero flow: (a) h_o is too low; (b) h_o is too high.

***Operational Note**: To determine the best offset, select Offset 1 under the Offset Manager in the Rating Development Toolbox (RDT). Adjust the offset iteratively with the scroll button until the measurements fall along a straight line. For finer precision, adjust the increment value (Offset Step) to 0.001.*

***Operational Note**: Every range to which a different offset applies must be separated by a break point. This allows the Rating Development Toolbox to provide a unique representation of all ranges while using different scale offsets. AQUARIUS does not allow the use of more than 3 independent offsets. When entering a second offset, a breakpoint is automatically created. Its location defaults to the lowest rating point. Rating points identified as breakpoints are greyed out in the Rating Table and can no longer be moved. Breakpoint 1 is associated with Offset 2. Breakpoint 2 is associated with Offset 3.*

[30] Le Coz 2014
[31] Sauer 2002, p.49
[32] Hydrology Project 1999, p.10

1.2.4.2 Survey

The second method for estimating the *offset* is through surveying. For a section control, the gauge height of zero flow can sometimes be directly surveyed. This *offset* should then correspond to the observed lowest point measured on the section control cross-section relative to the local datum.[33]

For a channel control, the *offset* can only be estimated by measuring the water depth at the deepest point at any cross-section along the channel reach and subtracting this depth from the stage at the hydrometric station at the time of the measurement.[34]

1.2.5 Defining the Equations' Applicable Ranges

The number of equations (segments) used in a rating and the range of each equation are defined iteratively. Measurements should plot linearly if they belong to the same segment. The plot of selected measurements (see Section 1.2.3.3 Graphical Representation) is thus inspected to identify where the structure in the overall model appears to change.[35] A change in rating structure should relate to some change in the characteristics of the control. Reviewing control cross-section survey information may thus help decide which range should be assigned to a segment.

An inability to align measurements on a straight line is often a good indication that a different range or number of segments is required, or that the *offset* was not properly defined. However, it can be difficult to define the range over which a single control dominates when only sparse and irregularly distributed measurements are available.

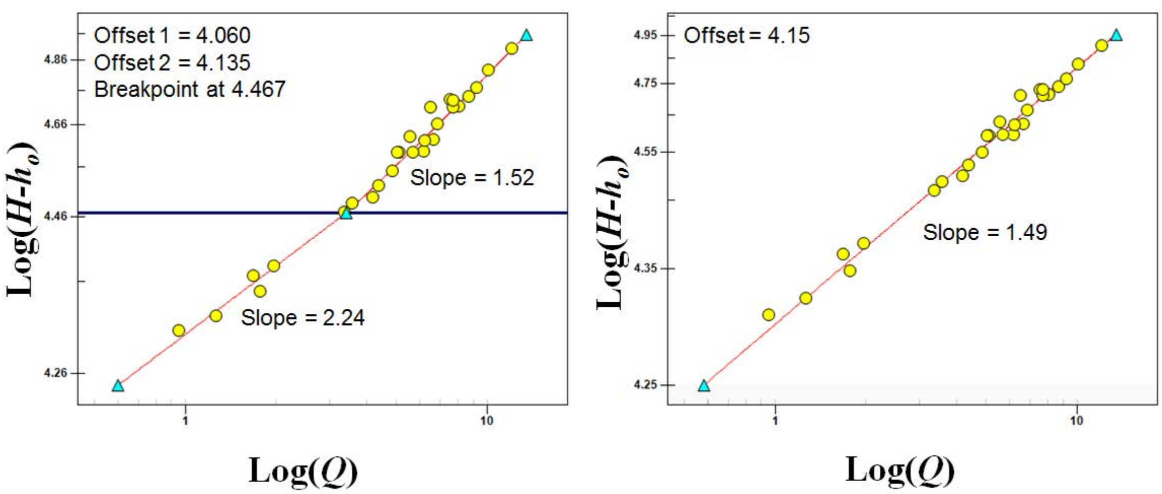


Figure 5. Example of rating (Horseshoe River above Lois Lake) initially specified with multiple segments (left) even though an adequate fit can be developed using only one segment (right). A surveyed elevation for the offset may help to identify the most suitable rating option.

1.2.6 Calibrating the Rating Equations

Once the expected range and *offset* (h_o) of each segment have been defined, their rating exponent b and coefficient C must be calibrated. In logarithmic scales, the *Computation Lead* must select coordinates for two rating points marking the lower and upper limit of each segment. The coordinates of these rating points are adjusted until:

- The line connecting two rating points fits the selected measurement sample. A line fits the sample if measurement errors appear uncorrelated and randomly distributed. This can be verified by examining a residual plot of the measurements compared to the rating (See section 1.2.6.1 Residual Plots). Note that if

33 NEMS Steering Group 2016, Section 2.2.4
34 NEMS Steering Group 2016, Section 2.2.4
35 Hydrology Project 1999, p.11

the sample size is too small, any departure from the desired normal distribution will likely remain undetected.

- The rating equation parameters respect the known hydraulic constraints. The rating exponent b parameter should fall near the range of values suggested by the control geometry (See section 1.1.4 Rating Exponents). Between consecutive segments, a significant change in this parameter will occur when there is a substantial change in the type of control governing the rating relation. See the example in Figure 2.

***Operational Note**: In AQUARIUS, in the Rating Development Toolbox, a line is automatically created between two successive rating points. The slope and intersect of this line (b and $\log(C)$) are adjusted by moving the points until they provide an accepted fit to the data.*

1.2.6.1 Residual Plots

Residual plots are useful to judge the goodness-of-fit of a rating model. Regression residuals e_i are defined as the difference between the i^{th} observed discharge value Q_i and the corresponding rated discharge value q_i.[36]

$$e_i = Q_i - q_i \ . \qquad (1\text{-}3)$$

Residual plots help to illustrate complex aspects of the relation between a potential rating and the selected measurements. Factors that contribute to the calibrated parameters' uncertainty can be identified through inspection of the residuals.[37] Essentially, residuals should be independent of one another and evenly distributed, exhibiting no structure or trend with stage or time. A model is a good fit to the data if most residuals are small.[38]

The following examples of typical shapes and possible causes should be kept in mind during the development of a rating (Refer to Figure 6):[39]

- In Figure 6-a, the fit seems adequate as measurements appear randomly distributed about the model.
- In Figure 6-b, the variance in discharge is not constant but depends on stage, indicating higher uncertainty at lower stages.
- In Figure 6-c, the rating seems to fit data well except for an outlier. In some cases (see Figure 6-d), such outliers may greatly influence parameter calibration.
- Information displayed in Figure 6-e may relate to 3 scenarios.
    - o The number or range of segments assumed to describe the rating structure is incorrect or has changed.
    - o Other independent variables (including time) may influence the stage-discharge relation.
    - o A nonlinear relation could exist between stage and discharge.

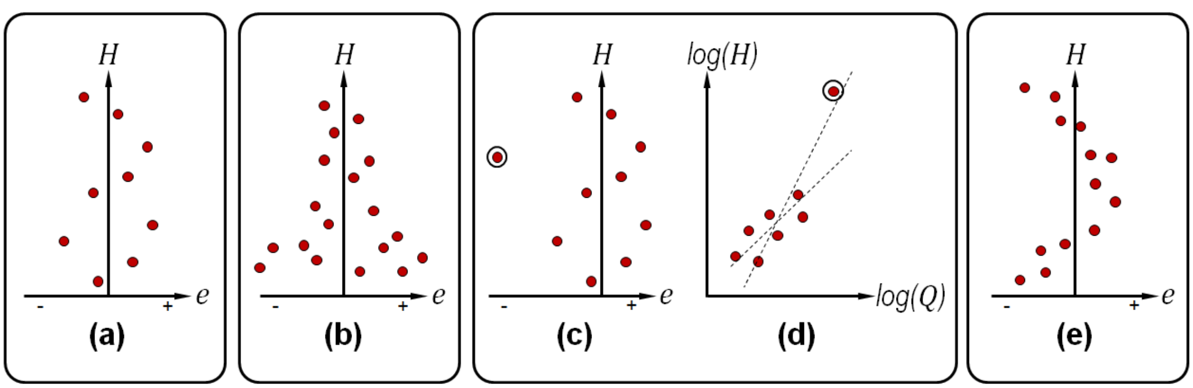


Figure 6. Examples of structures seen in residual plots and stage-discharge relations. (Adapted from: Devore 2000)

[36] NIST/SEMATECH 2012
[37] Devore 2000, p.548
[38] Devore 2000, p.498
[39] NIST/SEMATECH 2012

The *Computation Lead* should inform the supervisor if further investigation is required to determine the ability of a rating to accurately predict discharge. If desirable, discharge residuals can also be plotted by observed discharge, measurement date, or even calendar day of year. This could help reach a conclusion if trends in residuals are for example the result of a change in the sampling method (e.g. using a different measurement technology) rather than a characteristic of the control.

***Operational Note**: In AQUARIUS, the Shift Diagram is similar to the residual plots shown in Figure 6. Stage is on the vertical axis which helps interpretation of stage-discharge relations. Also note that residuals displayed in AQUARIUS are calculated as the difference between observed and the rated stage.*

1.2.7 Calibrating the Transitions

When a rating requires more than one equation, a *transition* between each segment is required. Each *transition* should ideally be supported by a physical change in the control. *Transitions* from a section control to a channel control may be obvious while *transitions* between two channel controls may not. Often, physical changes in the channel do not result in a different or unique equation. *Transitions* are not themselves defined according to any simplified hydraulic equation.[40]

Transitions should be calibrated only once the segments have been defined and the need to transition from one segment to the next is required. In many cases, a single common point is adequate to describe the end of one segment and the start of another. Where more defined transitions are required, more rating points can be added to properly describe the area. Ideally, larger *transitions* are interpolated using additional rating points to fit measurements available in the *transition* range. The upper and lower rating points then mark the *transition* zone limits while they also define the segments outer limits. Whatever strategy is used to define a transition, avoid modifying any of the calibrated parameters for segment above or below it if possible.

If empirical information is limited, *transitions* should be created in ways that will smoothly join consecutive rating segments. The *transition* range should then be made large enough to help in that respect. Additional rating points defined within the *transition* zone will provide the flexibility required to smooth the *transition* without changing any calibrated segment. However, an abrupt change between well-defined controls may sometimes be justified. The information and interpretation supporting such conclusion should be carefully documented as part of the model hypothesis in the *Station Analysis*. See section 1.4

[40] Sauer 2002, p.40

Rating Metadata for details.

***Operational Note**: Break points should mark the middle of any transition zone connecting segments governed by single controls. Data above or below break points are displayed using different offsets.*

1.2.8 Identifying any Estimated Range

Few rules dictate when a rating range should be identified as Estimated. Interpretation is once again essential. The decision to grade a rating as Estimated is based on an assessment of the quality and distribution of available measurements as well as the information describing flow conditions, including previous ratings, control stability or other historical details. The decision to identify a range as estimated rests with the supervisor, based on recommendations from the *Computation Lead*.

In general, consider grading part of a rating as Estimated when:

- it could not be calibrated using sufficient and adequately distributed measurements (See section 1.2.3.2 Sample Size);
- it was developed using estimated or non-standard measurements (e.g., mid-section discharge measurement based on less than 20 panels);
- it is used to produce data while still not *approved*;
- A part of it extends above twice the highest valid measurement. This upper part should be graded as Estimated. See section 1.3.2.1 Extensions.
- A part of it extends below half of the lowest valid measurement. This lower part should be graded as Estimated. See section 1.3.2.1 Extensions.

1.3 Maintenance

Existing ratings must be regularly reviewed against new observations. This review is the responsibility of the *Computation Lead*. It follows the same general strategy as the development of a new rating (see section 1.2) with minor variations meant to validate previous decisions, or identify required corrections. The maintenance process involves 5 general steps:

1. Review the assumptions made during the rating development to determine if they still apply.
2. Select and plot any new measurement along with the previously selected ones.
3. Assess whether all observations still plot linearly (in logarithmic scales) based on previously defined *offsets* and segment ranges.
4. Assess the goodness-of-fit of the rating.
5. Decide if a correction, a change of rating or an extension is required.

Throughout each of these steps, it is again essential to properly document any decision and its justification as part of the *Station Analysis*. See section 1.4 Rating Metadata for details.

***Operational Note**: In AQUARIUS, it is recommended to clone a curve before starting any review work on it. Since there is no locking mechanism in the Rating Development Toolbox, this will ensure that previous work is not tampered with.*

1.3.1 Shifts

Stable controls are regularly affected by minor random fluctuations.[41] They may vary gradually or abruptly because of changes in the physical features forming the control.[42] Such fluctuations are detected from time to time during discharge measurements conducted at hydrometric stations. Shifts are used when changes to a rating are assumed to be temporary and flow conditions are expected to later return to the norm.

1.3.1.1 Definition

A shift is an adjustment to the current rating rather than an entirely new stage-discharge relation. Shifts are used for temporary changes or during a period of time when more measurements are collected to define a new rating. Shifts can be prorated gradually over time to accommodate slow changes, such as the growth of aquatic vegetation.[43]

The magnitude of a shift is expressed in percentage difference of discharge or in stage difference. When expressed in percentage difference of discharge, shifts are the ratio of the difference between the measured discharge ($Q_{Measured}$) and rated discharge (Q_{Rated}) against the rated discharge.

$$\text{\% difference against the rating} = \frac{Q_{Measured} - Q_{Rated}}{Q_{Rated}} \times 100 \qquad (1\text{-}4)$$

When expressed in stage difference, shifts are the difference between the mean gauge height corresponding to the rated discharge (HG_{Rated}) and the measured mean gauge height ($HG_{Measured}$). This value represents the correction of water level that would be required to make the observed conditions fit the modeled predictions.

$$Shift = HG_{Rated} - HG_{Measured} \qquad (1\text{-}5)$$

***Operational Note**: In AQUARIUS, the shift expressed in stage difference corresponds to the value called Shift (m) while the shift expressed as a percentage is called the Rating Error (%).*

1.3.1.2 Methods

Shift corrections can vary over stage, time or a combination of the two. There are three accepted types of stage variable shifts, which are the “Constant”, ”Knee Bend” and ”Truss” methods. Any shift method can be

[41] WMO 1044 Vol.1, p.II.1-19
[42] WMO 1044 Vol.1, p.II.1-19
[43] Spehar 2013

applied as time variable, changing either abruptly or gradually over time. This section describes the recommended shift methods.

1.3.1.2.1 Constant

Constant shifts are applied when departures from the base rating are assumed to persist over their entire range in stage. Constant shifts often relate to changes in the gauge height of zero flow (e.g., simple scouring events). Ratings corrected with a constant shift are parallel to the original rating when plotted on arithmetic scales. When plotted on logarithmic scales, they are either concave upward and above the original rating for any deposition type change, or concave downward and below the original rating for any scour type change.[44] The application of a Constant shift requires only a single input point defined by the departure in discharge measured against the base rating, which is the same for all stages.

Operational Note*: To facilitate the analysis of results and thus approvals, Constant shift entry values should be associated with the water level and time of the measurement to which they correspond.*

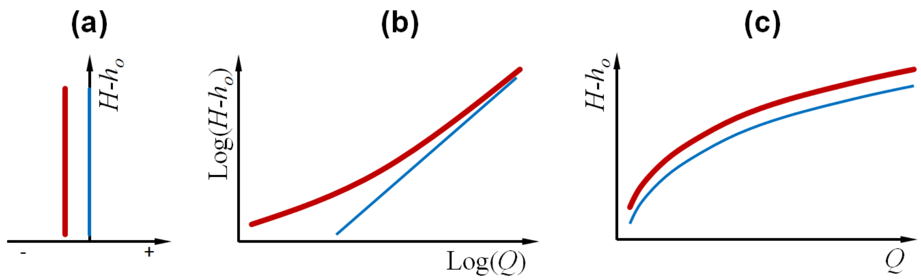


Figure 7. Example of Single Point shift (a) plotted against residuals, (b) plotted on logarithmic scale, and (c) plotted on arithmetic scale. The shift is displayed in red while the original curve is blue.

1.3.1.2.2 Knee Bend

Knee Bend shifts are used for rating corrections that vary as a function of stage. They are typically used to adjust the lower part of a rating, the section control, while the upper end remains unchanged. Knee Bend shifts should seldom be used to adjust channel controls. Knee Bend shifts are advantageous when stage is highly variable during the period when a correction is required as they then automatically adapt to the station current condition. This shift method is thus well suited for *Continuous Data Production* under variable conditions.

The application of a Knee Bend shift requires two input points:

- The higher of the two points can be called the Anchor Point. It defines the stage above which a rating is assumed to remain unchanged. This point typically coincides with the *transition* between a section and a channel control.
- The lower point is called the Knee Bend Point. It defines the stage below which the shift intensity is the greatest and remains constant.

If the cause of shifts is assumed to be recurring at the site, it may be possible to define Anchor and Knee Bend Points constant in elevation over many shift episodes (See Figure 9). Some seasonal influences may regularly affect a rating and do so in ways that are similar year after year. If so, the elevation of the Knee Bend Point could be defined using historical data. While the shift intensity then varies according to site visit results, the stage associated with a Knee Bend Point would be constant between consecutive shifts. The Anchor Point would itself be defined by the control characteristics. Since the shifts affect the same riffle control, they should share commonalities in their transition back to the base rating despite the fact that measurements used to define them were made at different stages.[45] Such an approach creates a family of shifts which helps to bring consistency between shift corrections. Note that conditions do evolve and shifts should be adapted to any new evidence.

[44] ISO 1100-2, p.13
[45] Kenny 2013

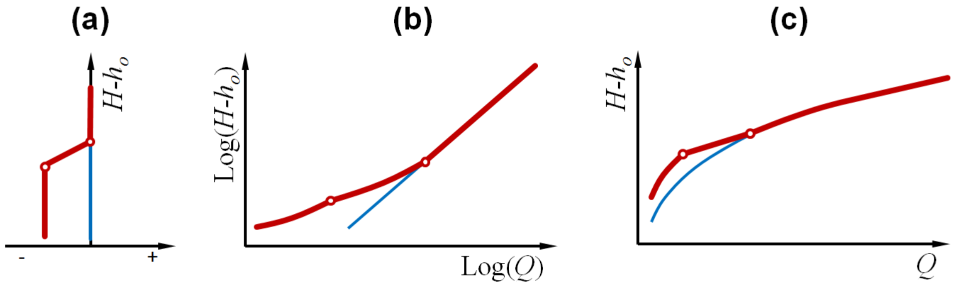


Figure 8. Example of Knee Bend shift (a) plotted against residuals, (b) plotted on logarithmic scale, and (c) plotted on arithmetic scale. The shift is displayed in red while the original curve is blue.

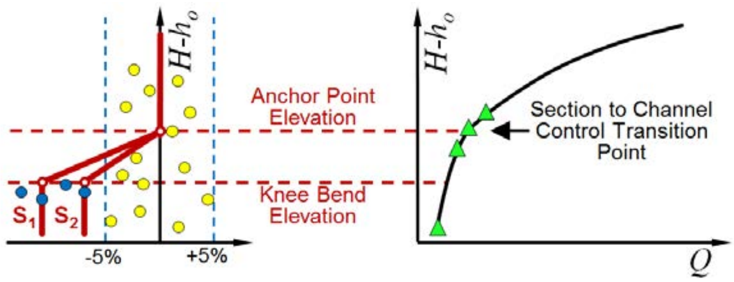


Figure 9. Example of Knee Bend shifts (S_1 and S_2) defined using the family of shifts concept.

1.3.1.2.3 Truss

Truss shifts are used when departures from a base rating vary with stage but return to the norm above and below a specific disturbance. Truss shifts have advantages similar to Knee Bend shifts and are required for cases such as a tree falling across a channel or the slumping of a river bank. Truss shifts are typically applied to the region between a section and channel control.

The application of a Truss shift requires three input points:

- The lowest point defines the stage below which the rating is assumed to remain unchanged.
- The middle point defines the shift maximum intensity. The shift correction recedes away from the maximum change above and below the specified stage value. This middle point in a Truss shift is typically set to the average elevation of the rating disruption.
- The upper point defines the stage above which the rating is again assumed to remain unchanged.

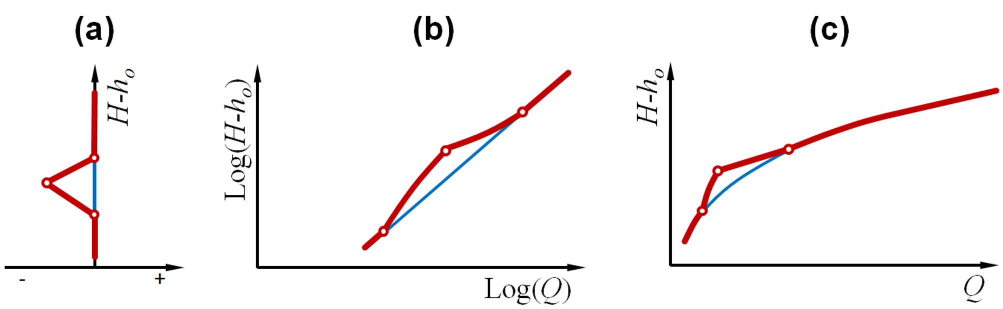


Figure 10. Truss shift (a) plotted against residuals, (b) plotted on logarithmic scale, and (c) plotted on arithmetic scale. The shift is displayed in red while the original curve is blue.

1.3.1.2.4 Time Variable

The intensity of a shift correction may change over time. It is therefore necessary to define its start and end time. It is also necessary to determine how the shift intensity is expected to evolve during that period. Be aware that since a shift start and end may be triggered by different phenomena, these transition periods may behave differently.

The intensity of a shift correction can change gradually or abruptly. When gradual, the correction intensity is pro-rated between two dates. During this period, it varies linearly between pre-defined shift values. It could for example evolve from zero to the difference observed during a station visit. When abrupt, the change in intensity takes place at a single point in time. It is not prorated but is assumed to appear or disappear instantaneously.

***Operational Note**: The pro-ration of one shift to another is controlled by its specified end date. If no end date is entered, this tells AQUARIUS that the adjustment should start with the initial shift intensity and progressively blend into the intensity defined by the next shift. By entering an end date, it is assumed that the shift is constant, that conditions are stable during the entire shift period. AQUARIUS will then apply the same shift intensity until the end of the specified period.*

Gradual shifts typically correspond to vegetation growth or decay, or steady siltation or erosion. This sort of transition may occur over weeks or months. If many discharge measurements were obtained during the transition period, a progression curve can be defined by plotting shifts through each available measurement. However, for this technique to apply there should be no sign of any flushing event between the measurements used to define the progression curve.[46]

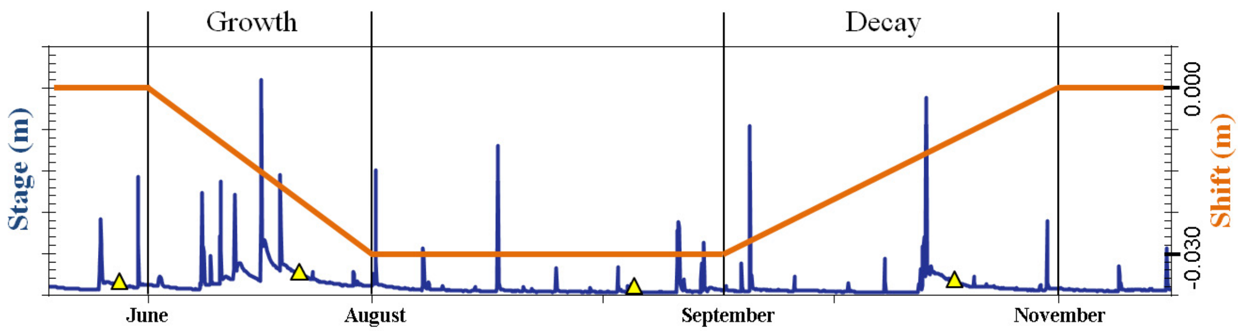


Figure 11. Representation of a gradual shift suspected for growing and decaying algae at a station control. The orange line indicates the shift intensity at any point in time. It starts at zero to reach -0.030 m at the end of the growing season. Interpretation was based on 4 measurements. The blue line is the stage recorded at the station.. Such condition would normally only affect the section control.

Shifts caused by sediment transport during flood events are also gradual. Their progression is relatively fast, typically taking only a few days. Such shifts begin when the stream velocity is sufficient to mobilize bed or bank material (usually when the *hydrograph* is rising most rapidly) and end when stream velocity drops sufficiently for bed load movement to cease and deposition to occur (typically around the inflexion point of the falling *hydrograph*, see Figure 12). If multiple flood peaks occurred, it is acceptable to assume that the transition took place over the entire event. If there are several candidate peaks, it is acceptable to choose the largest.[47]

[46] NEMS Steering Group 2016, p.25
[47] NEMS Steering Group 2016, p.25

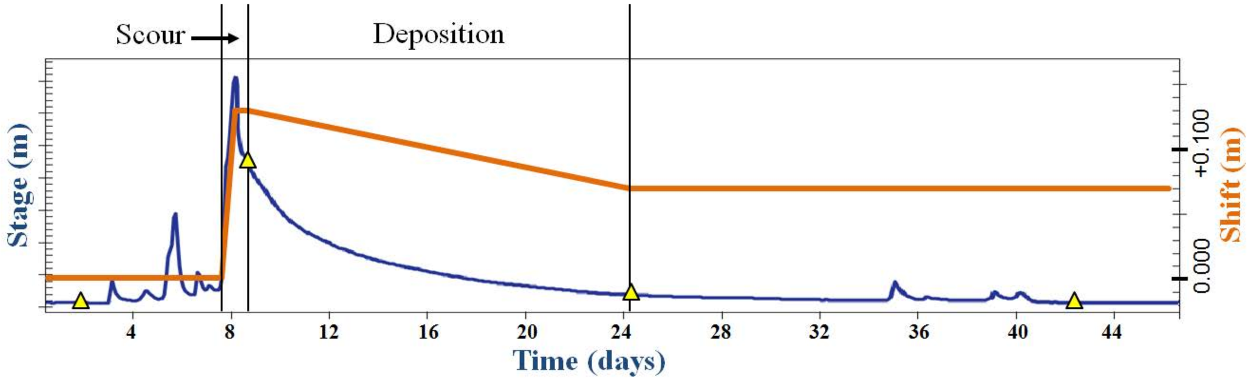


Figure 12. Representation of a shift progression suspected during a flood event with scour and deposition. The orange line indicates the shift intensity at any point in time. The blue line is the stage recorded at the station. Based on observations, scouring was assumed to start on the fast rise and reach its maximum intensity at the peak. After the high water measurement, the shift was then assumed to recede and match the measurement obtained during the recession limb. As the shift appears stable, the last measurement may indicate that a new rating is desirable.

Abrupt shifts usually correspond to steps in data that can be observed in the time-series or significant events known to have affected station records. A shift is often abrupt when caused by human and beaver activities (e.g. removal of debris on the control) or catastrophic events such as major floods or large objects falling on the control (see Figure 13).

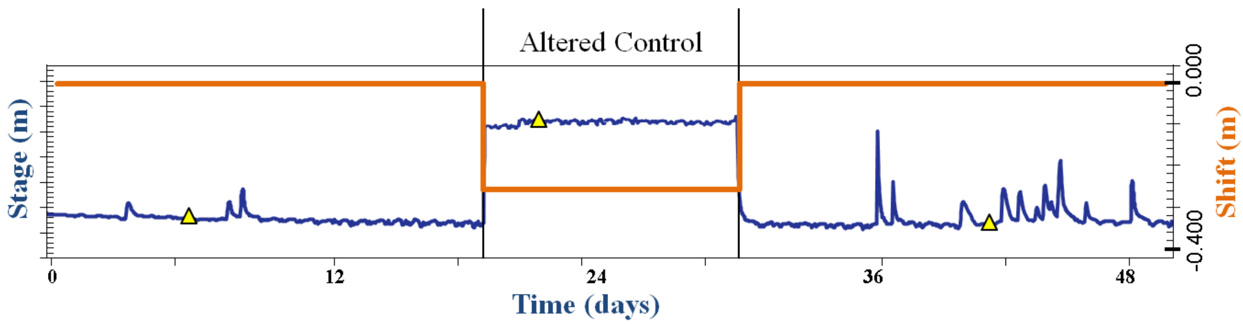


Figure 13. Representation of an abrupt shift caused by sand bags piled on the control by a road construction crew. The orange line indicates the shift intensity at any point in time. The blue line is the stage recorded at the station.

1.3.1.3 General Shift Process

The analysis of shift corrections assumes that a stable base rating was previously established at the site.[48]

First, the *Computation Lead* must gather all available information. This information should include the following, for the period under investigation, as well as recent and similar flow periods:

- Hydrometric Survey Notes, including discharge measurement details
- Stage time-series
- Meteorological data
- Hydrographs from comparable stations
- Previously applied shifts.

Based on gathered information, the *Computation Lead* should then identify, design and apply shifts according to the following steps:

1) Detection
2) Design
3) Documentation and Application

[48] WMO 1044 p.II.1-19

1.3.1.4 Detection

Note that since field information is essential for the detection of shift periods, a higher frequency of site visits is recommended during periods of rating instability.[49]

To detect the need for a shift, the *Computation Lead* must first determine if there is any difference between rating predictions and field observations. If the measurement plots outside of a range of tolerance, then further investigation is required to confirm and design the required shift.

1.3.1.4.1 Difference against the Base Rating

The difference between a discharge measurement and its rated value is used to detect the need for a shift. It is calculated according to the equation described in section 1.3.1.1 Definition.

Using this difference assumes that the base rating is more accurate than any single unverified measurement. However, any measurement verified by a *check measurement* is considered more accurate than the corresponding rated value.[50] Any digression from these working assumptions must be recorded in the Station Analysis.

The need for a shift is suspected when a measurement does not fall within some specified interval against the base rating. More specifically, the rules are that:

1) A shift should be considered if a discharge measurement is outside 5% of the rated discharge and greater than 0.003 m of the rated stage, and an associated *check measurement* confirms such result.
2) When the result of a measurement and its *check measurements* do not agree, the *Computation Lead* must investigate site conditions and measurement quality to determine if the deviation is due to hydraulic instability, measurement error or calibration error. The *Computation Lead* must then decide whether or not to apply a shift and if it should be based on any specific measurement or on the average of multiple measurements. Remember that measurements typically include bias and random errors. Also, significant scatter in measurements plotted against a rating may not indicate the need for a shift, but instead a level of complexity that could not be handled with the simple rating approach.[51]
3) No shift should be considered if a discharge measurement is within 5% of the rated discharge, or within 0.003 m of the rated stage.

If a shift is suspected, the conditions observed during the site visits, signs observed in the station *hydrograph* and shifts previously applied must then be considered to corroborate and help define the shift that is required.

1.3.1.4.2 Conditions Observed During Site Visits

The Hydrometric Survey Notes should be reviewed to identify any hydrological, geological or biological influences that may have affected control conditions. Channel and control conditions observed during site visits may offer clues about the necessity to apply a shift, and the most probable cause for any suspected control change. See section 1.4.3.1 Control Conditions. Such clues could for example include a change in control geometry from debris or a change in channel conveyance due to vegetation growth.

1.3.1.4.3 Atypical Hydrograph Patterns

Station *hydrographs* should be examined to detect periods of rating instabilities. The design of a shift should account for recent regional hydrological and climatological influences. It is sometimes possible to observe unusual shapes in a *hydrograph* when recent data are examined against expected trends. It is recommended to always cross-check signs observed in the *hydrograph* with meteorological data. Unusual shapes might be related to significant flow events, such as a rise in stage during a recession period in the absence of rain, or a step associated with debris flushed from a control. These details may not define the intensity of a shift, but could provide useful hints about the start or the end of a period of rating instability.

[49] NEMS Steering Group 2016, p.23
[50] WMO 1044 p.II.1-19
[51] NEMS Steering Group 2016, p.23

1.3.1.4.4 Previous Periods of Rating Instability

Periods of rating instability should always be evaluated in a context greater than any single site visit. This is important to determine if a previous shift still applies, and to base the detection on lessons from historical site conditions and control behavior.

The design of a shift should account for historical hydrology, climatological influences and past decisions about shifts. The methods used to design and apply previous shifts should thus be investigated to ensure continuity in results, or question and improve them. Previous shifting events may still apply during the currently investigated period. A trend in consecutive measurements, plotting either all to the left or to the right of the base rating, may also show that the original rating was not well defined and must therefore be improved.

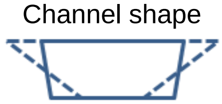
1.3.1.5 Design

To design a shift, the *Computation Lead* must articulate a hypothesis which will then serve to define how the shift should vary as a function of stage and time.

1.3.1.5.1 Shift Hypothesis

A justification based on hydraulic principles as listed in Table 2 must be provided for every shift applied. It is important to clearly articulate what the assumed cause and effect of a shift are, so they can be debated during the *peer review* and approval of data. Shifts are rating curves. The shift hypothesis should therefore relate identified or suspected changes in hydraulic factors to suggested modifications to rating equation parameters. See Table 2 for a generic description of hydraulic factors to consider, and how such factors would affect rating parameters. This information is provided to help *Computation Leads* enunciate a cause and effect hypothesis for any shift applied. The shift hypothesis must be documented in the *Station Analysis*. See section 1.4 Rating Metadata for details.

Table 2. Interpretation of change in rating equation parameters based on change in controlling hydraulic factor[52]

Relevant Hydraulic factor	Parameter affected	Effect	Example
Channel slope 	Coefficient	Increase in channel slope increases coefficient	A large slug of sediment that stalls upstream of the gauge could cause an increase in local channel slope.
		Decrease in channel slope decreases coefficient	
Channel roughness 	Coefficient	Increase in channel roughness decreases coefficient	As they grow, weeds may reduce the conveyance capacity of a channel by altering the stream bed frictional resistance.
		Decrease in channel roughness increases coefficient	
Bed elevation 	Offset	Increase in bed elevation increases *offset*	In a simple aggradation event, sediments accumulating on the streambed would result in higher water level for any channel location.
		Decrease in bed elevation decreases *offset*	
Channel shape 	Rating Exponent	Tendency toward a more triangular channel shape increases the exponent	Debris cumulating on a control would effectively change its cross-sectional shape.
		Tendency toward a more rectangular channel shape decreases the exponent	

1.3.1.5.2 Intensity as a Function of Stage

The *Computation Lead* must select a shift method that matches observed variations in discharge relative to stage (deduced from available measurements) and which agrees with suspected shift cause and effect (shift hypothesis). Based on the range of measurements recently collected, define the shift intensity (departure against the base rating) for various stage values. While all shifts are temporary conditions by definition, in

[52] Hamilton 2015, p.6

some settings a shift may be stable enough to be measured at more than one stage.[53] Determine if the detected shift is expected to remain constant or vary relative to stage. For details on applicable shift methods, see section 1.3.1.2 Methods.

When recurring shift characteristics are suspected to apply, such as Anchor and Knee Bend Points, the *Computation Lead* must review historical shifts to define such input values.

Always inspect the overall shape of a shift against the base rating. Again, remember that shifts are ratings and as such should respect the known control characteristics and their effect on the stage-discharge relation.

1.3.1.5.3 Progression Relative to Time

The progression of a shift is defined as the way it should be applied as a function of time between two identified dates marking its start and end. Note that understanding the shifting characteristics of a particular station is important in selecting the proper timing of shifts.[54]

Determine whether the shift is likely to appear or recess gradually or abruptly. To do so, review the conditions observed during site visits, atypical *hydrograph* patterns and previous periods of rating instabilities (see section 1.3.1.4 Detection). If no information can permit the identification of any particular shift progression, the shift should then be pro-rated from start to end.

Match the shift progression onto possibilities offered by suspected or identified causes. The shift start and end should not be anchored only to available measurements dates. The signs suspected to mark periods of rating instability on the *hydrograph* should also be considered for the shift start and end. To do so:

1. Identify the dates of suspicious patterns in the station *hydrograph*.
2. Identify the dates of meteorological events known to influence flow, such as precipitations or droughts and temperature fluctuations.
3. Assess whether any suspicious *hydrograph* pattern could be explained by the identified meteorological events.
4. If another *hydrograph* from a comparable station is available, also assess whether any pattern is similar and thus likely not attributed to local rating instability.
5. Finally, eliminate the most unlikely start and end date options.

As a result of this analysis, there may be many options to explain when and how the shift should be propagated. The *Computation Lead* must then list the most likely options, identifying the one which was retained and recommended. This information must then be documented in the *Station Analysis*. See section 1.4 Rating Metadata for details.

1.3.1.6 Application

Based on information deduced during the detection and design of a shift, its expected behaviour relative to time and stage should now be well defined and documented. These characteristics are then used to apply the rating correction.

The following guidance should be considered when applying a shift:

1) A shift must be regularly monitored and re-assessed to determine if it still applies. A more permanent rating revision should be considered for shifts lasting many seasons.
2) Shifts should not be over-designed, describing more than available information allows.
    - o Constant shifts are not always appropriate for multi-segment ratings. However, when visits are frequent enough and stage fluctuations are small, these shifts may be as effective as complex ones while easier to justify and quality control.

[53] Kenny 2013
[54] Kenny 2013

- o It is never appropriate to develop a shift using residuals alone, without reference to the base rating.[55] Always review the shape of any recommended shift against the base rating and its control features to make sure that the shift remains true to the basic hydraulic principles that it describes.

3) No shift should be considered if a discharge measurement is within 5% of the rated discharge, or within 0.003 m of the rated stage.
   - o A 5% uncertainty is assumed by WSC for any flow measurement performed according to standards. Measurements that fall within 5% of a base rating indicate that a shift at that stage is not necessary.
   - o A 0.003 m uncertainty is assumed by WSC for any stage measurement. Measurements with a corrected mean gauge height that falls within 0.003 m of the rated stage indicate that a shift at that stage is not necessary. Low flow discharge measurements are very sensitive to noise and scatter. They should only be used to refine the overall shape of the base rating as part of a larger statistical sample.
   - o If a shift is applied despite the conditions stated above, the reasons must be documented in the *Station Analysis*. See section 1.4 Rating Metadata for details.
4) A shift should not be applied if it is only supported by a single measurement and it is not substantiated by any other observation or historical information justifying such a decision.[56]
   - o A *check measurement* should always accompany any measurement that departs significantly from expected results.
   - o Observed control conditions and a documented history of rating instability can justify the application of a shift based on a single and unverified measurement. However, such a decision must be documented in the *Station Analysis*. See section 1.4 Rating Metadata for details.
5) Assuming flow conditions will remain stable, shifts can be extrapolated into the future as steady corrections.
   - o Shifts are difficult to design in *real-time*, while rating instabilities are still evolving. The design of a shift should be revisited and adjusted as soon as additional information becomes available. Great care must be applied to regularly monitor flow conditions between visits to make sure that changes in conditions do not go unnoticed, possibly causing an undesired step in data.

Operational Note*: In AQUARIUS, the Field Visit Table in the Rating Development Toolbox lists “R Error %” which indicates the percent difference between the measurement and the current un-shifted rating curve, and “S Error %” which is the percent error between the measurement and the selected shifted rating curve. This information should be used to guide the interpretation and application of shifts.*

1.3.2 Revisions

Rating curves evolve. They must be regularly reviewed and possibly revised when permanent changes have been detected. They may require extensions to cover ranges initially not defined, or their general shape may have to be modified.

1.3.2.1 Extensions

The range of stage and discharge values covered by a rating curve should coincide with the range of values observed at the station location. However, if discharge needs to be calculated at stages outside of the previously observed or expected range, the rating should be extended.

For complex extensions, the *Computation Lead* should review the best practices described in the manual on “Extension of Rating Curves at Gauging Stations” (Ramsbottom and Whitlow 2003) which is available in the WSC Library.

A high degree of uncertainty is associated with ratings used outside of their calibrated range. Rating extensions should therefore always be validated with alternative sources of information. They should also be identified, thus graded as Estimated, when appropriate.

[55] Kenny 2013
[56] NEMS Steering Group 2016, p.24

1.3.2.1.1 Upper End

Upper end rating extensions should not go above twice the highest valid measurement and/or cross into a new control condition, such as a flood plain. This is because an extension can be defined as a straight-line projection of the highest rating equation parameters only if the control geometry and channel roughness are assumed to remain constant over this range of stage.

Indirect measurement techniques should be considered in order to define and validate upper end extensions. The World Meteorological Organization's Manual on Stream Gauging, Volume II – Computation of Discharge (Section 1.11, WMO-No. 1044, available in the WSC Library) describes such techniques in detail. Indirect measurement techniques include:

- the conveyance-slope method;
- the areal comparison of peak runoff rates;
- flood routing;
- the step *backwater* method.

1.3.2.1.2 Lower End

Lower end rating extensions should not go below half of the lowest valid measurement. If the section control seems to apply all the way to zero flow, it may be acceptable to extend the lowest rating equation parameters towards a lower point in stage. However, at extreme low flows, the stage-discharge relations are often subjected to many control influences and may not conform to any specific equation. The lower end of a rating may also be affected by instrument precision limits which increase calibration uncertainty. See section 1.3.1.6 Application.

The lower end of a rating should be treated as a *transition* zone if no equation is assumed to apply in its lower range. It is then recommended to simply draw a line through the average of low flow measurements and the estimated point of zero flow instead of attempting any straight-line extrapolation of rating parameters.

Note that only nil values must be published as discharge data when the stage goes below the point of zero flow. Stage data should then also be removed from *publication* to avoid any confusion among data users. Raw stage data are always available to *Computation Leads* if ever required, such as to confirm the connectivity of a gauge pool with the stilling well.

Operational Note: *In the Data Correction Toolbox, an automated deletion (open-ended) should be applied to the stage time-series in order to remove any data at or below the assumed point of zero flow.*

1.3.2.2 Modified Segment

The validity of a rating used at a gauging station must be confirmed during every *approval period*. The process to decide and then modify any part of a rating (segment) is the same as the one described in section 1.2

Rating Development Strategy.

Note that when a new rating is developed to replace an existing one, the new rating must be compared to the old one to verify that any notable difference between the new and the previous ratings are justified and reasonable.[57]

[57] Spehar 2013

1.4 Rating Metadata

A rating description must be associated and provided with any rating. This information includes details on its development, validation or correction. It is required by users and reviewers to help understand model limitations and possibilities of improvement.

Ultimately, the Rating Metadata must be captured in the *Station Analysis*, for the period during which the work was performed. For ratings, this corresponds to the start of their period of applicability. Depending on their length and complexity, shifts may have to be described in more than one *Station Analysis* to properly cover the influence of their start and end on data.

1.4.1 Identification

The identification of ratings is managed according to the following rules:

- New ratings at a gauging station are chronologically assigned identification numbers by increments of 1. For example, Rating 12.00 would have been developed after Rating 11.00.
- Ratings retain their original identification number as long as they are unchanged. A rating is modified when any of its parameters (C, b and h_o) or *transitions* has been changed.
- The identification number originally assigned to a rating must never be changed.
- The rating numbering sequence must not be broken.
- The same identification numbers must not be used for different ratings at the same station.
- A new identification number must not be assigned to a rating simply because a new period of applicability has been assigned to it, even if this new period is non-contiguous.

The identification of rating extensions follows a special rule:

- Extended ratings share the same identification number as their parent rating but are chronologically assigned a decimal value by increments of 0.01. For example, Rating 11.01 would be the first extension for Rating 11.00. Such extended ratings are considered to be part of a family of ratings which shares similar equation and *transition* characteristics. This special numbering is meant to help identify and review rating extensions. It applies if the rating has been extended upward, downward or on both ends at once.

***Operational Note**: In AQUARIUS 3.6, changing the grade on any part of a rating will affect any data previously created with this rating. As such, ratings affected by a change in grade are to be identified using the same rule as extended ratings.*

1.4.2 Description

The following details, which describe how and why a rating was developed, as well as issues to consider during its validation, must be included in the Rating Metadata:

- Implementation
  - First start date for the rating's applicability.
- Rationale
  - Justification for and purpose of work performed on the rating, such as for a newly established station, a change in control or an extension.
- Complexity
  - Assessment of whether or not a simplified hydraulic equation appears suitable for all conditions expected at the site.
- Structure
  - Description of the segments and *transitions* expected to account for cross-section properties (geometry, geology or vegetation) and control types (section, channel, flood plains), including a description of the point of zero flow or *bankfull* stage.
- Stability
  - Description of local factors that may occasionally or regularly modify the relation.
- Estimated Range

  - Description of why parts of the rating are considered ill-defined and have been graded as estimated.

1.4.3 Associated Measurements

The following summarized information is the minimum information that must be available to reviewers for all measurements which influenced the development of a rating and thus be included in the Rating Metadata: [58]

- Date and time
- Total discharge
- Corrected mean gauge height
- Magnitude and direction of stage change (positive for rising stage, negative for falling stage)
- Control conditions
- Comments

***Operational Note**: The selection of measurements displayed during the development of a rating cannot be preserved (locked) within the AQUARIUS software itself. The Computation Lead must therefore manually save information on measurements used to develop or validate a rating. In AQUARIUS, measurement details can be exported as a comma delimited file (Rating Development Toolbox, Field Visit Table, functionality called 'Export as .csv'). This information can then be summarized and listed as part of the rating metadata and, ultimately, in the Station Analysis.*

***Operational Note**: The magnitude and direction of stage change that occurred during a measurement can be displayed in AQUARIUS, as part of the Time Series View available in the Rating Development Toolbox.*

1.4.3.1 Control Conditions

Good notes on control conditions observed during (not deduced after) a site visit are essential to any rating and shift analysis. Such notes, which may include pictures, will help decide if a rating change is permanent or temporary.[59] Comments must also specify to what degree the control was affected by observed conditions. A description of control conditions must therefore accompany every measurement and include:

- a general description of the control condition, selected among WSC standard categories (see below);
- remarks defining why the selected control condition is thought to apply, to what extent it appeared to be affected by observed conditions, and the possible effect that these conditions had on the flow.

Standard WSC categories for control conditions must be used to identify the main issue thought to affect a control. Note that some of the categories differ only in the way their effect might propagate over time.

The standard categories for control conditions are:

- Not Observed
  - No information was collected about the control conditions.
- No Flow
  - No water was observed passing through the control, although the gauging pool may not be dry.
- Clear
  - The control appeared free of any flow interference.
- Debris
  - Scattered fragments floated into or accumulated over the control.
- Altered
  - The control was modified because of human or animal activities.
- Weeds
  - Aquatic and land vegetation grew into the control reach.
- Fill
  - Increased control elevation caused by observed sediment deposition.
- Scour
  - Decreased control elevation caused by observed sediment erosion.

[58] WMO 1044 p.II.1-3
[59] Spehar 2013

- Ice
    - Ice was observed to obstruct flow within the control reach.

1.4.4 Associated Shifts

All shifts applied to a rating must be described in the Rating Metadata according to the following requirements:

- Shift Application Period
    - Start and (if available) termination date and time for the period affected by the shift.
- Shift Hypothesis
    - Description of the suspected shift cause and effect.
- Intensity as a Function of Stage
    - Statement justifying the choice of method (e.g. Knee Bend) used to define the shift as a function of stage.
- Progression Relative to Time
    - Statement justifying the choice of timeline used to apply the shift.

1.5 Rating Implementation

When implementing a rating, consider client expectations as well as operational requirements to determine how and when a rating and the corresponding discharge data should be produced and published. Depending on the station objectives, it may be preferable to wait for more certainty in the rating before disseminating any product, or it might be desirable to publish *provisional* or estimated product as early as possible.

To conform to WSC rules for significant figures and decimal places, no rating must be defined at a precision smaller than 0.001 m^3/s for discharge or 0.001 m for stage.

1.5.1 Period of Applicability

A Period of Applicability defines a time interval over which a rating is deemed functionally stable and can be used to produce data. A single rating can have multiple Periods of Applicability and these periods do not have to be adjacent to one another. The assignment of a new Period of Applicability does not constitute a change of rating and therefore does not require the assignment of a new rating identification number. All Periods of Applicability ever assigned must be identified and documented within the rating metadata (See section 1.4 Rating Metadata).

A rating can be removed from service or brought back into production as many times as site conditions justify it. The reasons why an older rating was reinstated must, however, be specifically described and explained in the *Station Analysis*. See section 1.4 Rating Metadata for details.

Operational Note*: In AQUARIUS, be aware that a rating is used in data production as soon as it is assigned a Period of Applicability.*

1.5.2 Transition between Ratings

Prior to any implementation, the start of a new rating Period of Applicability must be recommended by the *Computation Lead* and be *approved* by the Supervisor. The recommended date must allow a smooth transition from any previously used rating. If a discontinuity in the discharge time-series cannot be avoided during such a transition, the magnitude of this discontinuity must be less than 5%. If it is necessary to actively smooth the transition between ratings, it should be done through the application of a shift on either side of the transition point.

If a rating revision was triggered by long lasting shift corrections, then the initial shifted rating will be comparable to the newly updated base rating. Under such conditions, the transition between a shifted and new rating should coincide with a site visit to help avoid any step in derived data. It is then unlikely that any additional shift will be required to smooth the transition.

Operational Note*: The blending of rating curves is a technique used by some hydrometric agencies to distribute differences in outputs from two adjacent ratings. This technique was developed as an alternative to shifts when conditions cycle through recurring ratings. The technique of blended ratings is not to be used within WSC. In AQUARIUS, a blended rating is created when two rating periods are overlapped in time. In version 3.6, also note that AQUARIUS allows operators to change an approved period of applicability. Operators have to use extreme caution as this could inadvertently create a blended rating and result in changes to approved data.*

Although corrections could be applied to the derived discharge time-series in order to remove any perceived step in data, this is not the recommended solution. It will not adapt to any subsequent change in data or models. A correction of the discharge output could then become inadequate and cause errors difficult to monitor and correct.

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