Quality Assurance Monitoring Plan

Streamflow Gaging Network

by
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Environmental Assessment Program
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Olympia, Washington 98504-7710

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Abstract

Management of surface water in Washington State requires a streamflow measurement network capable of monitoring water diversions, minimum instream flows, and water availability, as well as detecting trends in all parts of the state. The Department of Ecology operates a streamflow gaging network program focused on obtaining information for water resource management needs. This document presents detailed information on each of the 14 elements required of a Quality Assurance Monitoring Plan. Any changes to methods or evaluation approaches described in this plan will be updated on Ecology's website.

Background

Management of surface water in Washington State requires a streamflow measurement network capable of monitoring water diversions, minimum instream flows, and water availability in all parts of the state. Both the Washington State Department of Ecology (Ecology) and the U.S. Geological Survey (USGS) operate streamflow gaging programs focused on providing basic data to address water resource management needs. The management needs identified by Ecology's Water Resources Program include the Instream Resource Protection Program (IRPP), the Water Acquisition Program, and streamflow trend information to help manage natural and human-caused changes to Washington's available water resources (Adelsman, 2003).

Water resources management needs in Washington State are also specifically defined in the Watershed Health and Salmon Recovery Monitoring Act. Directed by this law, state agencies prepared the Comprehensive Monitoring Strategy (CMS) for monitoring watershed health and salmon recovery statewide. The Strategy and action plan were submitted to the Governor and the Legislature (IAC, 2002). The CMS identified specific questions for which streamflow monitoring information was needed. All these indicators require the monitoring of continuous flow.

The monitoring activities developed by Ecology's Stream Hydrology Unit (SHU) are designed to help answer the management questions described above.

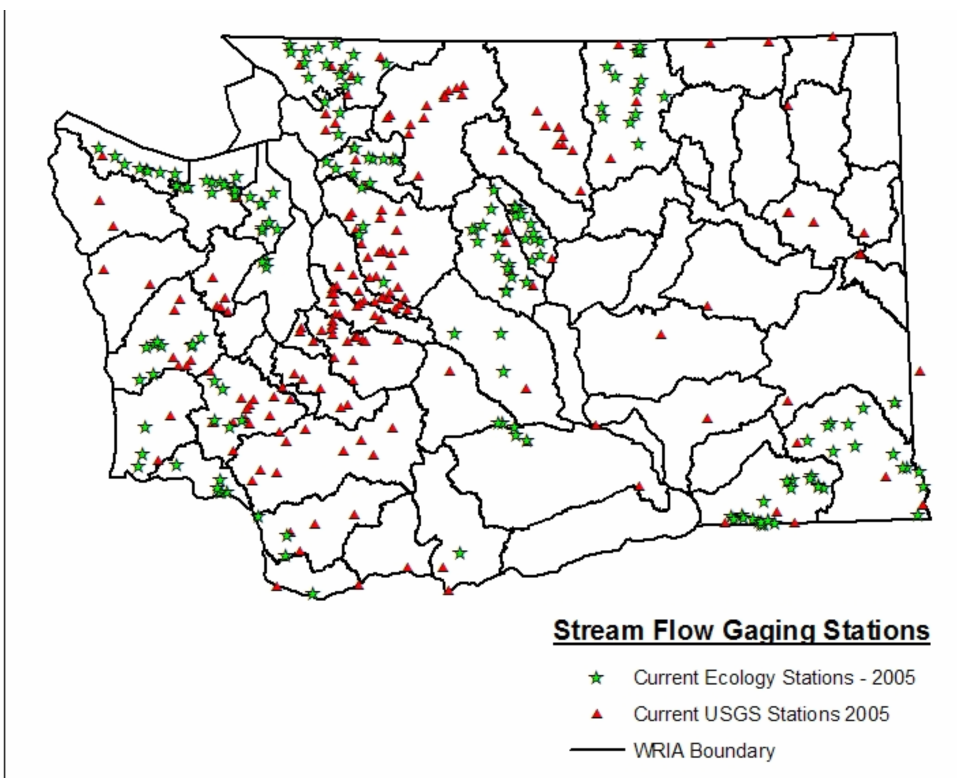

Figure 1. Washington State's Streamflow Monitoring Network

Project Description

The Stream Hydrology Unit provides streamflow information in support of various statewide instream and out-of-stream planning and management efforts, such as watershed planning, water resources management, flood plain management, Total Maximum Daily Load (TMDL) evaluations, and ambient fresh water monitoring studies. In addition, accurate and timely streamflow data are critical in defining and implementing salmonid recovery efforts.

During Water Year 2005, Ecology monitored streamflow at 189 stations in many critical basins where salmon populations are impaired. The SHU works with local partners to expand the streamflow gaging network to both improve the state of existing knowledge about flows in the watershed and support multiple water and watershed management initiatives.

The operation of Ecology streamflow stations falls into three types: telemetry, stand alone, and manual stage height.

Telemetry

Ecology currently operates 93 telemetry gaging stations. A telemetry station logs stage height every 15 minutes and transmits this data in three hour blocks to the Ecology Headquarters in Olympia, Washington, via a GOES satellite transmitter or a standard dial-up modem. This data is automatically imported into the streamflow database and published to Ecology's web site.

Stand Alone

Ecology currently operates 35 stand alone gaging stations. A stand alone station logs data every 15 minutes and is downloaded periodically (typically once a month). Data is imported into the streamflow database manually and automatically published to the Ecology web site. Stand alone stations are typically operated for up to or less than one Water Year (October 1 - September 30). However, many of the stand alone stations have been in place for many years. Streamflow data from both active and historic stand alone stations are included on the Ecology web site.

Manual Stage Height

Ecology currently operates 61 manual stage height gaging stations. A manual stage height station does not produce a continuous record but is typically only a single point in time measurement. Stage height is directly read from either a standard staff gage, wire weight gage, or measured from a reference point. Reference points and wire weight gages are located over the wetted width of the station cross section from which a measurement can be made to the water surface.

Stream height measurements taken at all three types of stations are converted to instantaneous streamflow using a rating table or flow curve. Rating curves for each of these stations are built based on the relationship between a series of periodic stage height measurements and their corresponding instream flow measurements.

Organization

Ecology's Environmental Assessment Program (EA) is organized into "units" where staff focuses on specific functions, including monitoring of streamflow. The SHU has 14 hydrologists and environmental specialists that provide streamflow information in support of various statewide instream and out-of-stream planning and management efforts.

Personnel	Phone	General Duties
Brad Hopkins	360-407-6686	Unit Supervisor
Bruce Barbour	360-738-6249	Field Assistant
Steve Butkus	360-407-6742	Assessment and Modeling
Howard Christensen	360-407-6479	Field Assistant, Maintain Flow Stations
Casey Clishe	360-407-6691	Maintain Flow Stations
Chris Evans	360-407-6052	Maintain Flow Stations, Real-time GOES Acquisition Data Management
Don Fisher	360-407-6321	Field Assistant
Art Larson	360-407-6560	Special Projects
Jim Peterson	509-454-7865	Maintain Flow Stations
Jim Shedd	360-407-7025	Senior Review and Quality Assurance
Kelsey Sinclair	509-575-2825	Maintain Flow Stations
Chuck Springer	360-407-6997	Database Administrator, Maintain Flow Stations
John Summers	360-407-6022	Maintain Flow Stations

Quality Objectives

There are two types of quality objectives that need to be identified: Measurement Quality Objectives (MQOs) and Data Quality Objectives (DQOs). MQOs are "'acceptance criteria' for the quality attributes measured by project data quality indicators. [They are] quantitative measures of performance…" (USEPA, 2002). MQOs are the targets for precision, bias and sensitivity against which laboratory QC results are compared. Precision is assessed from the results of replicate analyses of samples and standards. Bias is . . . from method blanks, check standards and matrix spikes to their expected values. Sensitivity is related to the detection and reporting limits for the measurement method used.

Streamflow data are based on field measurements. While there is no reference standard for streamflow data, some components of bias and precision in the measurements can be evaluated and controlled as described under Measurement Procedures and Quality Control Procedures. SHU has not yet collected sufficient quality control data prior to this writing to evaluate the actual error attained to set MQOs at this time. SHU will establish specific MQOs over time as more quality control data have been collected to better define acceptable precision, bias, and accuracy.

DQOs are needed in projects where the results are compared to a standard or used to select between two alternative conditions. Ecology's streamflow data are used for the following purposes:

1. Ecology's Freshwater Quality Ambient Monitoring Program.
2. Watershed Lead Entities establishing instream flow rules.
3. Salmon Recovery Funding Board support of the Intensively Monitored Watershed Program.
4. Water quality modeling needed to establish Total Maximum Daily Loads (TMDLs).
5. Water Acquisition Program support.
6. Other specific projects conducted with local cooperators.
7. Evaluating trends in streamflow.

DQO's have not been specified by the clients for the first six programs. However, we assume that meeting the DQO for the last listed purpose (i.e., trend detection) will also enable the data to be used for these other purposes.

DQO's can be established to address statistical requirements for trend analysis. Linear trend analysis is a form of hypothesis testing of the model (Lettenmaier, 1977):

$$Y_t = \mu + \Delta\mu * t/t_l + \varepsilon_t \quad 1)$$

where,

y_t = the value of the monitored water quality variable at time, t
μ = the mean at the beginning of the time period
$\Delta\mu$ = the change in the mean over the time period,
t_l = the length of the time period,
t = the time elapsed since the beginning of the time period,

ε_t = a stochastic error term.

The hypothesis to be tested is:

H_0 (null hypothesis): $\Delta\mu = 0$ (no change in the mean value), and
H_a (alternate hypothesis): $\Delta\mu \neq 0$ (a change has occurred).

The size of trend ($\Delta\mu$) that can be detected depends on the degree of confidence one desires in one's conclusion, the number of independent samples collected, and the variability in the data. Power, confidence level, and sample size are related so that both α (the probability of detecting a change when one has not occurred, *i.e.*, falsely rejecting the null hypothesis – type I error) and β (the probability of not detecting a change when one has occurred, *i.e.*, falsely failing to reject the null hypothesis – type II error) decrease with increasing sample size. Also, when one chooses a smaller α (*i.e.*, one assumes a stricter criterion before rejecting H_0), β increases (assuming sample size stays the same). Given values for α, β, and sample size (n), one can calculate the magnitude of the trend that can be detected relative to the standard deviation of the data.

The DQO is the specified magnitude of the trend that we wish to detect. SHU has set the desired trend magnitude ($\Delta\mu$) to five percent of mean annual streamflow. Because the ability to detect trends is related to the variance of the data, separate DQOs for trend detection have to be determined for different streamflow gaging stations. Depending on the variance measured at a particular station, DQOs may also have to be specified for different ranges of streamflow (i.e, for trends in peak vs. minimum flow). SHU has not yet collected sufficient quality control data prior to this writing to evaluate the actual error attained to set DQOs at this time.

Monitoring Design

Management often asks technical staff to provide a comprehensive assessment of all surface waters in the state. It is simply not possible to monitor the quantity of all waters statewide using a “census” approach (e.g., monitoring every surface water flow). A “sample survey” approach is often used to conduct comprehensive statewide assessments. A sample survey approach allows for the estimation of the conditions of waters statewide by making inferences from a defined set of monitoring locations. The level of certainty for these estimates can be described.

Sample surveys are intended to produce assessments of the condition of the entire resource when that resource cannot be subject to a complete census. Sample surveys rely on the selection of monitoring sites that are representative of the resource. EPA (1997) describes two different sample survey designs: probability-based and judgmental. Both designs use a stratified sampling method so inferences can be made about other waters the samples represent, with a known level of certainty. These two types of monitoring designs are described below.

The *probability-based design* uses monitoring stations that are selected in a statistically random method. Randomization in the site selection process is the way to assure that sites are selected without bias. This approach is used to select stations for EPA's Environmental Monitoring and Assessment Program (EMAP).

The random selection of stations provides:

- Every possible station (population) has a known probability of being selected for monitoring (sample).
- The set of stations monitored (sample) is drawn by some method of random selection, or a systematic selection with a random start.
- Estimates are made about the population from the sample.

The use of a probability-based design has several drawbacks for use in the water quantity assessment. The most significant is the need to establish a new sampling network based on random selection. With this design, one cannot use data collected by an existing sampling network. Also there are much higher costs associated with traveling to remote stations that may have limited access. This site selection approach will only work for natural run-of-river systems with no withdrawals.

Judgmental design is the other sample survey approach recommended by EPA (1997). Selection of monitoring locations is based on the best professional judgment that the sites are representative of the target resource (i.e., a subpopulation of surface waters). The method assumes that the stations selected represent all waters in a particular subpopulation. Monitoring station locations from an existing sampling network are periodically reviewed individually to determine the reasons why the location was selected.

The judgmental design has several advantages:

- All stations selected are accessible.
- All sites are suitable for accurate flow measurements.
- Allows the making of estimates with a known precision and confidence.
- Data collected by existing and historical stream gaging sites can be used.

However, there are some deficiencies in the judgmental design:

- Assumes those stations selected by judgment represent all waters in the watershed.
- Watershed estimates may still be biased due to factors unknown when selecting sites using best professional judgment.
- Complications arise from unknown surface to groundwater interactions resulting in gaining and losing stream reaches.

Based on an assessment of the advantages and deficiencies of each design, SHU uses a judgmental sample survey design for assessment of streamflows.

Measurement Procedures

In order to meet the general objective of providing a comprehensive assessment of surface waters in Washington State, Ecology's Stream Hydrology Unit's (SHU) major tasks in support of this objective are to accurately measure and monitor stage height, perform accurate instantaneous streamflow measurements, and produce reliable ratings in order to predict flow throughout the entire range of stage over time on a particular stream. In addition, SHU must maintain continuous reporting of data in near real time on the Internet.

SHU has implemented procedures designed to successfully perform these tasks. In addition, methods have been developed to addresses the quality of equipment performance, discharge measurements, flow ratings, field procedures, and continuous data records. Discharge is measured using the field protocols described below. Streamflow is estimated from the relationship of multiple discharge measurements collected along a stream cross section.

All continuous records, ratings and related data are stored in the SHU database (Hydstra®) and, where appropriate, the relevant results are published on the SHU website www.ecy.wa.gov/programs/eap/flow/shu_main.html.

Field Procedures

In addition to specific methods, SHU has several procedures for ensuring consistent and useful field notes. Field notes should be as legible and thorough as possible. All relevant conditions should be described in field notes. Proper operation of the equipment and any measurements, observations, adjustments, or required actions should be noted. These notes should be copied to the Hydstra® Data Workbench, in case field notes are lost, as well as for easy reference as data is evaluated. The field notes will be reviewed at the end of the Water Year and major issues highlighted in annual technical note summaries. These annual technical note summaries will be posted on the SHU website.

Time

Pacific Standard Time (PST) is used year round. During Pacific Daylight Time one hour is subtracted to arrive at standard time. The letters PST should be appended to all times in the field notes to reduce ambiguity. All entries in the SHU database will be in PST.

Site Visits

Upon each site visit, at the very minimum, a staff gage or other primary stage observation is noted. At sites where additional parameters are recorded such as air and water temperature, appropriate quality checks are made and noted against the manual instruments measuring these parameters. During most site visits the latest data set is downloaded from the data logger to a laptop or hand held computer. If a stream discharge measurement is conducted during the visit, data should be downloaded at the conclusion of the measurement.

Measuring Stage Height

SHU currently uses four methods to establish stage height: reference points, wire-weight gages, staff gages, and continuous stage-height recorders. Explicit instructions for each method are included in SHU Field Protocol's document. Each station should employ at least two of these methods to verify stage data records, verify field observations, and provide alternate stage measurement capabilities, should other methods become precluded. Staff gages and reference points should be surveyed for relative elevations (referenced to a known benchmark) upon installation, and re-surveyed, when cross sectional and thalweg surveys are conducted or channel-altering flow events warrant additional surveys.

Staff Gage

A staff gage is a graduated measuring device securely fixed to a permanent structure in the streambed from which river stage height can be read directly to 0.01 feet. Where the seasonal change in stage is great, it may be necessary to set additional staff gages at surveyed elevations up the stream bank to accommodate a variety of stream levels.

Reference Point Measurement

A reference point is a fixed point or datum on a bridge or other structure from which a measurement can be taken on the surface of the water under all flow conditions. Measurements taken from a reference point are the reverse of true stage height. A longer distance from the reference point to the water surface corresponds to a lower stage height and vice-versa. The distance from this reference point to the water surface is measured with a weighted fiberglass measuring tape. The weighted tape is lowered to the water surface just to the point where the wake from the water passing by the weight forms a slight distinctive "V" shape. The distance from the reference point to the water surface is recorded to the nearest 0.01 feet.

Wire Weight Gage

A wire weight gage is a self-contained measuring device that is permanently attached to a bridge. It consists of a weighted wire that can be cranked up and down on a spool. Measuring stage height with a wire weight gage is similar to a reference point measurement. However, the wire weight gage is more accurate than a weighted fiberglass tape and the reference point for a wire weight gage is within the gage box itself. In addition the wire weight gage is reverse calibrated, meaning it expresses a direct measurement of stage as opposed to a reference point measurement, which is an inverse measurement. The wire weight is lowered to the water surface just to the point were the wake from the water passing by the weight forms a slight distinctive "V" shape. The distance to the water surface is recorded to the nearest 0.01 feet.

Continuous Stage Height Recorders

A continuous stage height recorder measures and records the stream stage at preset time intervals. Data loggers are used to record and store the measured stage data. The data loggers are generally programmed to record stage at 15-minute intervals.

Two types of devices are used to measure stage. These devices, located at a fixed instream location, measure relative water column pressure. One type of device, an electronic instream pressure transducer, measures water column pressure directly. The other, a pneumatic type of device, uses an external (out-of-stream) pressure transducer to measure the amount of air pressure at varying stages needed to emit a bubble from the end of a pneumatic orifice line. Both types of devices convert the column pressure to a digital value. Regardless of equipment type, the measurement precision is always at least 0.01 feet.

Stream Discharge Measurement

Stream discharge measurements are performed regularly on the streams SHU monitors. Discharge measurements are done initially at new sites to establish a rating curve. The objective is to measure as wide a range of flows as possible to construct a rating curve that accurately predicts flow at the widest possible range of stage.

After a reliable rating has been established the rating must be regularly updated and verified with additional flow measurements. The physical structure of a streams channel changes over time. Depending on hydraulic conditions in the stream, the channel can be altered by sediment deposition or erosion. These changes in channel geometry and structure often alter the stage flow relationship expressed through the rating. As a result, flow measurements should be done relatively frequently throughout the Water Year. In particular, measurements should be done immediately following a large flow event to verify the validity of the rating. If there is evidence the rating has shifted, follow up measurements should be done as soon as possible to establish the new rating.

SHU currently uses four basic methods to measure stream discharge. The most common method is done by wading an instream cross section. A second method is measuring streamflow from the deck of a bridge. A third method, is measuring flow from a boat. The fourth method involves the use of an Acoustic Doppler Current Profiler (ADCP). Each of these methods requires specific specialized equipment and procedures. The method selected depends on the width, depth, and velocity of the stream and other physical conditions. All methods, with the exception of the ADCP, involve selecting an appropriate cross section, dividing the cross section into segments, and determining the depth and velocity of the water passing through each segment. Use of the ADCP also requires appropriate cross section selection but does not require division of the cross section into segments. SHU uses the USGS mid-section method for all flow calculations. Explicit instructions for each discharge measurement method are included in the SHU Field Protocol’s document.

Selecting a Cross Section

The selection of a suitable stream cross section is very important and cannot be over emphasized. Site selection is, in most cases, the most important factor in developing accurate flow information. The limitations of a poor cross section can not be overcome by the quality of equipment or the ability of the individual taking the measurement.

The following characteristics should be present at an ideal cross section:

1. The stream course should be relatively straight and free flowing for 200-300 feet both upstream and downstream of the measurement site. The sites should be free of excessive turbulence.
2. The stream channel should be free of vegetative growth and be relatively stable (free of major seasonal scouring or deposition of bed material).
3. The stream bed should be relatively uniform with only minor irregularities (no large cobble or boulders).
4. During low flow conditions (typically Aug-Oct) the stream channel should be confined to a single course.
5. The stream bank should be stable and able to contain the maximum measurable streamflow.

Ideally the cross section to be measured will meet all of the selection criteria, however, some do not. If the cross section selected is compromised by excessive aquatic plants, the presence of woody debris, or has minor irregularities in the streambed (rocks and manageable boulders), an attempt should be made to minimize their impact on flow measurements. This may require physical removal of interference and minor alterations of the streambed with the aid of a garden rake or shovel.

After the cross section has been cleared the stream banks are inspected to ensure they are confining enough to provide a distinct edge. If the streambed has a gentle sloping bank, rocks or other available material can be used to make a defined stream edge. Care should be taken to insure that minimal water by-passes these structures. Do not change the section after starting a measurement as this will alter the flow characteristics and, therefore, the accuracy of your measurement. Field notes describing the cross section and any notable characteristics are vital when determining the subjective professional rating of the discharge measurement. The location of the cross section is marked on the bank to ensure the exact location is used in future streamflow measurements. Using the exact location is important to help detect changes in channel geometry due to peak flow events that can shift the rating curve.

Dividing the Stream Channel into Segments

Streamflow is calculated by summing individual discharge measurements through pre-determined segments of the cross section. A measuring tape (tagline) is stretched across the stream perpendicular to the cross section to be measured. The tape is anchored to the surrounding vegetation\debris or to stakes driven in for attachment points. Width of the stream channel is noted and divided into measurable segments. The segments should be divided such that approximately five percent and no more than ten percent of the total flow is within any one segment. In most cases stream cross sections would be divided into approximately 30 segments. Measuring points should be closer together in portions of the cross section where flow is more concentrated and where velocity or bottom irregularities are the greatest.

Measuring Velocity of Stream Segments (wading and mechanical bridge measurements)

When stream discharge is measured by wading or with the use of mechanical bridge or boat measuring equipment, velocity is measured with a velocity meter at each pre-determined segment across the stream. There can be significant variability in stream velocity measurements. Velocity varies horizontally across the cross-section and vertically through the depth strata of the cross-section. Velocity also naturally "pulses" in streams at any single location over short periods of time.

Horizontal Velocity Variation

Channel geometry, substrate, flow controls, and other stream features cause horizontal variability between stream segments. Field staff can minimize *horizontal velocity variation* by applying these guidelines.

- Distribute measurement points across the channel to capture the variability of horizontal stream velocity. Divide the stream cross-section into about 30 segments. Concentrate the distribution of segments where velocity is highest and in areas where significant velocity variation can be identified. It is acceptable to measure fewer segments if previous discharge measurements show the cross-section and velocity distribution is uniform.

Vertical Velocity Variation

In most natural stream conditions, a logarithmic relationship exists between velocities through the depth strata of the water column. Typically velocity increases in the upper portion of the water column and decreases near the bottom. Address *vertical velocity variability* within a segment using one of the following methods, depending on measurement conditions.

- **Six-tenths method:** Use the six-tenths method in stream segments less than 1.5 feet in depth. Sample velocities at sixth-tenths of the depth from the water surface. Assume velocity samples at six-tenths of depth represent the average velocity through the depth strata up to 1.5 feet. Use the six-tenths method at all depths when stage is fluctuating rapidly and the measurement must be made quickly.

- **Two-point method:** Employ the two-point method in streams with depths greater than 1.5 feet. Velocities are sampled at two-tenths and eight-tenths of the depth, and the results are averaged. Because of the design of mechanical equipment used to measure from a bridge or a boat, the six-tenths method is used at depths up to 2.5 feet when measuring discharge from a bridge or a boat. The two-point method is used in depths greater than 2.5 feet when measurements are conducted from bridges or boats.
- **Three-point method:** In situations where a logarithmic relationship does not exist between strata of velocities through the water column, use the three-point method. Presume a non-logarithmic relationship exists when the two-tenths velocity is two times or greater than the eight-tenths velocity or the two-tenths velocity is less than the eight-tenths velocity. The three-point method consists of velocity samples at two-tenths, six-tenths, and eight-tenths of depth. Average the six-tenths sample against the mean of the eight-tenths and two-tenths velocity samples, weighting the six-tenths sample as half of the calculated velocity for the segment.

Single-Point Velocity Variation

Stream velocities in natural conditions tend to "pulse" or speed up and slow down over time at the same stage. These fluctuations compound the effects of horizontal and vertical velocity variability at fixed locations in the stream. Apply the following guidelines to address single-point velocity variability.

- Take 40-second velocity samples to address variations in velocity over time at a single measurement point. In the case of mechanical instruments, take two 20-second samples. Measure 40-second velocity samples at each measurement point except in situations when stage is fluctuating significantly or when very low velocities are sampled with mechanical instruments. In circumstances when stage is fluctuating, take single 20-second velocity samples to complete the discharge measurement quickly and to obtain a stage that reasonably represents the measured discharge. When using mechanical equipment, increase the sample time to 60 seconds when velocity is less than 0.5 feet per second.

Quality Assurance of Velocity Measurements

Wading discharge measurement will include a velocity quality assurance (QA) test. The QA test will consist of two components. The first component or the "start test" is done prior to the discharge measurement. This test determines if the Swoffer® (SHU's standard) equipment is of sufficient quality to be used for the measurement. A second or "post measurement test" is done after the discharge measurement is complete. This test will determine the overall velocity error in the measurement.

If the start velocity comparison is greater than ten percent, the standard propeller should be exchanged for another and retested. If the ten percent comparison cannot be achieved, the reference equipment should be used for the particular measurement. If the standard propeller fails to achieve acceptable results in two or three successive tests, or test results show consistently high margins of error, the propeller should be retired from service.

A post measurement QA test is done after the discharge measurement is complete. This test consists of two sets of velocity comparison measurements done between the standard and the reference instruments at a point that represents the estimated average velocity for the measurement. The comparison is considered acceptable if the velocity comparisons are within ten percent. If the difference between the standard and reference equipment is greater than ten percent another comparison should be done. If both post comparisons are over ten percent, the lesser of these two values should be reported.

To assess velocity accuracy, these tests are conducted against reference velocity equipment manufactured by Hydrological Services Inc., in Australia. The reference equipment is factory calibrated through the use of a tow tank in accordance with Australian standard AS 3778.6.3-1992. The Australian standard is identical with and has been reproduced from the international standard ISO 3455:1976.

The formula to determine the percent difference (PD) between the comparative measurements is:

$$PD = \left[\frac{S - R}{R} \right] x100$$

Where S = the mean of the standard measurements, and
R = the mean of the reference measurements.

Side by side comparisons between reference and standard velocity equipment are not practical in the case of discharge measurements from a bridge or a boat. An assessment of the propeller used in the bridge or boat measurement should be made before the measurement by examining past performance of the propeller in prior tests. The assessment of this error should be included in the subjective "professional" rating made in the field on the discharge note sheet.

Each set of reference velocity equipment is returned to the manufacturer for recalibration annually. Comparative assessments are done regularly between the reference equipment.

Detailed procedures associated with the quality assurance of velocity measurements are included in the Field Procedures Quality Assessment document.

Duplicate Discharge Measurements

The purpose of duplicating measurements is to assess the precision of SHU's discharge measurements and evaluate the techniques used to measure discharge. Each month, one randomly selected SHU staff member will perform a duplicate discharge measurement at a station within one of the projects or basins they are responsible for. The station will also be randomly selected.

Both discharge measurements will be considered "official" and the records of both entered into appropriate databases. For quality analysis purposes, a "start" velocity comparison will be done at the start of the first measurement and a "post measurement" comparison done at the conclusion of the second measurement. The staff member selected to perform the duplicate measurement should be the individual operating the measurement equipment.

A discharge measurement will not be duplicated if a significant stage change occurs or the site is inaccessible or unsafe. In those cases, the station next on the numerical station list will be measured (i.e. 46A160, 46A170, 46B060 etc.).

It is suggested that the cross section used in the first measurement also be used for the duplicate measurement. However, depth and velocity measurements should not be done at the same vertical location as they were in the first measurement. The verticals used in the second measurement should be off-set from those used in the first. For example, if the first vertical in the first measurement was at 2.0 feet and the remaining verticals were at two foot intervals, the duplicates first measurement might be set at 3.0 feet with two foot intervals.

In the case of bridge measurements, duplicates can be done simultaneously by taking two sets of notes as the bridge is traversed. The first set corresponds to the first measurement from a starting vertical at a given interval. The second set of notes corresponds to the duplicate measurement with the starting vertical offset from the first but at the same interval. With this method, the bridge equipment will not be moved unnecessarily.

The objective of duplicating measurements is to document the random variability inherent in the measurement procedure. The relative percent difference (RPD) is calculated and compared to the MQO of 5%. In addition the cross sectional areas and the average velocities of the two measurements should be within five percent. The following formula will be used to evaluate duplicate measurements:

$$RPD = \left[\frac{| R1 - R2 |}{R1 + R2} \right] x200$$

Where R1=Result for the first measurement
R2=Result for the second measurement.

Calculating Streamflow

A rating curve is developed that relates river stage height to instantaneous flow. Four to six times a year we take instantaneous flow measurements and corresponding stage heights. The rating curve is produced by plotting instantaneous flow measurements and stage heights. Provided the timing of these four to six instantaneous measurements cover the entire range of stage heights measured during the year, and the streambed has been unaltered by sediment deposition or erosion, a reasonably accurate rating curve can be expected. If the rating curve does not cover the full range of the stage recorded, the curve can be extended to equal twice the highest or ½ the lowest measurement recorded. Any extension of the curves beyond this will only be used to estimate flow, and the corresponding flow numbers will be qualified to signify they are only an estimate.

Temperature data

Temperature data collected by SHU is measured using two types of probes. The first is an internal thermistor within the submersible SDI-12 pressure transducer. The SDI-12 probe uses water temperature to correct for the change in pressure response due to temperature and adjusts the final pressure accordingly. The nominal accuracy of this built in thermistor is ± 1 degrees °C. However, our side by side comparisons with tidbit temperature probes have found the internal thermistors to be within ± 0.2 degrees °C. Stations where a self-contained bubbler is used to measure stage height have a separate thermistor probe for measuring water temperature. The nominal accuracy of these probes is ± 0.2 degrees °C. Both probe types are deployed within a 2" galvanized slant pipe that extends from the gage house into the stream channel.

Quality Control Procedures

The quality assurance and quality control procedures include two elements: 1) a written procedure manual, and 2) a method for tracking calibration of flow meters.

Written Procedure Manual

This QAPP documents the protocols for measuring streamflows. These protocols are reviewed semi-annually to ensure it remains current. All new personnel are issued a personal copy of the protocols to read before beginning field training by senior SHU staff. Annually, all SHU staff attends a field technique review workshop to ensure protocols are being correctly followed.

Calibration of Flow Meters

To maintain credibility with clients and the public, SHU must provide reliable and accurate streamflow data. To accomplish this, SHU regularly tests and calibrates equipment to insure they meet a high level of quality and dependability. The quality of the streamflow data generated by SHU depends on the accuracy of stage records and instantaneous flow measurements. The methods described below describe the approach used to assess the quality of stream velocity measurements with the use of calibrated reference instruments.

Velocity Measurement Quality Assurance

A stream velocity measurement quality assessment is best done in the field with equipment calibrated to an internationally recognized standard. In this manner our regularly used equipment, tested against the calibrated equipment, can be linked with this standard. During each stream discharge measurement a quality assessment is conducted with calibrated reference equipment tied to an international measurement standard.

The SHU has purchased precision engineered water velocity measuring instruments for the purposes of quality testing our regularly used Swoffer® equipment. This reference equipment, manufactured by Hydrological Services Inc. in Australia, is factory calibrated through the use of a tow tank in accordance with Australian standard AS 3778.6.3-1992. The Australian standard is identical with and has been reproduced from the international standard ISO 3455:1976.

Quality Assurance Field Procedures for Instream Velocity Measurements

Each and every discharge measurement includes a velocity quality assurance (QA) test. The QA test consists of two components. The first component, or the "start test", is done prior to the measurement. This test determines if the Swoffer® equipment is of sufficient quality to be used for the measurement. A second "post measurement test" is done after the discharge measurement is complete. This test determines the overall velocity error in the measurement.

Start Measurement Test

The start test is conducted for velocities between 0.50 feet per second (fps) and 1.00 fps. Before starting a discharge measurement, field staff assesses the stream velocity to determine the influence of velocities less than 0.50 fps on the discharge. Velocities below 0.50 fps have high error. The reference equipment should be used for the entire measurement when a large portion of the individual velocities are expected to be less than 0.50 fps. Referral to prior measurements may be needed to evaluate expected velocities. The yearly recalibration of the reference equipment far exceeds the manufacturers recommendations for maintaining meter accuracy for such infrequent field use.

The reference wading rod cannot measure velocities at depths less than 0.30 feet. Velocities at depths below 0.30 feet cannot be tested. A preponderance of depths less than 0.30 feet in a discharge measurement is addressed in a computer program explained in more detail below.

The 'start test' is simply a series of three velocity measurements taken with the standard equipment followed by three more measurements with the reference equipment at the same location instream at the same point in the water column. The mean of the three respective measurements is calculated and compared. If the standard velocity average is within +/- ten percent of the mean of the reference measurements, the discharge measurement may be conducted without further action required. The formula to determine the percent difference (PD) between the means of the comparative measurements is:

$$PD = \left[\frac{S - R}{R} \right] x100$$

where S = the mean of the standard measurements, and
R = the mean of the reference measurements.

If the start velocity comparison is greater than ten percent, both sets of equipment are examined for any defects or problems that can be remedied in the field. The location in the stream where the test is being conducted could also be a cause of faulty velocity measurements. Differences in the design of the two instruments can cause different velocity measurements particularly in shallow or highly turbulent water. After checking the equipment and re-locating the testing site if necessary, another start velocity comparison between the two instruments should be done. If the second comparison is not satisfactory then the standard propeller is replaced for a new one, and the new propeller tested in the manner described above. If the second propeller cannot achieve the ten percent threshold in two tests, the reference equipment is used for the entire measurement. Upon returning from the field, further tests are conducted on any standard propellers that do not pass the start test to determine if they need to be discarded.

Post Measurement Test

A post measurement QA test is done after the discharge measurement is complete. This test consists of two sets of velocity comparison measurements done between the standard and the reference instruments. This velocity comparison is done at a point that represents the estimated average velocity for the measurement. If the percent difference of the comparison is less than ten percent, the test is complete. If the difference between the standard and reference equipment is greater than ten percent, another comparison is done at a different location on the cross section, and the lesser value is reported. Only one post measurement comparison is required if the percent difference is less than ten percent.

The purpose of the multiple measurements based on percent differences is to minimize instream variability in velocity. The location in the stream where the test is being conducted could also be a cause of faulty velocity measurements. For example, obstructions in streams may cause turbulent flow increasing velocity variability. The 10 percent threshold is used based on the variability expected in the measurement protocol.

Calibration of the Reference Equipment

Each individual reference fan/meter assembly is returned to the Hydrological Services Inc. factory in Australia for re-calibration once per year or sooner if their performance is suspect. At approximately three month intervals, one individual fan/meter assembly will be sent to the facility in Australia for re-calibration.

The reference fan/meter assembly returned from re-calibration will be assumed to be the most accurate of our reference units and the standard against which comparative testing of the reference equipment will be measured. At the time the reference fan/meter are returned, all of the fans/meters are gathered for comparative testing against the returned fan/meter. The comparative testing consists of ten velocity measurements at three different velocities at the same point in the water column at each point of measurement. A reference meter is assumed accurate if the tested fan/meter assembly is within three percent of the standard. Reference meters that do not pass this test are cleaned, retested, and if necessary, returned for re-calibration. SHU maintains a record of calibration results.

New Swoffer® propellers are field tested to ensure they are of sufficient quality for field use. After field testing, the new propellers are numbered for identification and assigned to individual SHU staff. SHU maintains a record of propeller assignments including when it was placed in service, number of uses, and when the propeller was retired. The record includes the results of the comparative QA tests against the reference equipment.

Data Management Procedures

The Stream Hydrology Unit's data are managed in Hydstra®, a commercial database utility designed specifically for the management and analysis of hydrologic data. Manual calibration readings such as staff gage readings and handheld thermistor readings are entered into the database by the sampler. Duplicate stage readings are taken at each site using different methods (i.e. staff gages and bridge reference points). These readings are entered into the database by the investigator and validated by senior level staff during the review described below.

Flow measurements are calculated using Qwin, a flow calculator developed by Ecology. These measurements are reviewed by senior level staff and returned to the sampler to make any necessary adjustments or corrections. The flow measurements are then applied to the existing flow rating curve for the station to assess validity of the flow measurement, as well as any potential changes in channel geometry or velocity profile at the station.

Stage data is collected and imported into the Hydstra® database in two ways. The first is by using GOES equipped stations or Data Collection Platforms (DCP). These stations log data every 15 minutes and then transmit this data via the GOES satellite system in three hour blocks. These transmissions are received at Ecology Headquarters using an LRGS (Local Readout Ground Station) system. This receiver is located on the roof of the Ecology Headquarters building (Figure 2).

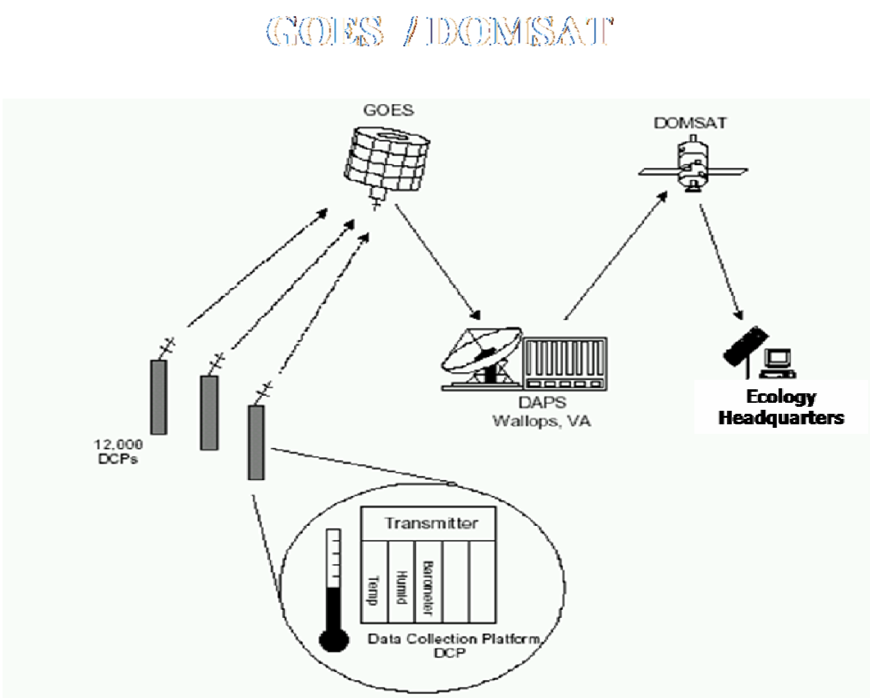

Figure 2. Telemetry Data Flow

At set intervals the GOES transmissions are processed at Ecology using DECODES, a commercial software package designed by Ilex Engineering, to filter and archive raw satellite transmission data. Decoded transmissions are then routed to a raw transmission file where the Hydstra® system processes the files every hour. The real-time web reports, seen on the SHU web page, are generated using these transmission files.

Data gaps are inherent to remote telemetry data collection. To fill these gaps a second method of data collection is used. A minimum of once every 4 to 6 weeks each DCP is visited by staff to download the logger files. Both the GOES equipped stations and the stand alone stations are downloaded in this fashion. These logger files are then manually imported into the Hydstra® database, effectively backfilling any data gaps for the GOES equipped stations and appending new data to the stand alone station files. These data sets are verified and adjusted to known observations on a quarterly interval. This is done by comparing the continuous data record to known field observations made by Ecology or local staff.

Continuous stage and temperature data are imported into the Hydstra® database by the sampler and checked for anomalies such as spikes and pressure-related noise. The data are coded as provisional and appended to the data archive for the station. At the end of the Water Year, continuous data are compared with manual readings taken at the station to assess instrument drift and the potential for erroneous readings.

Rating Development

The stage/flow relationship is expressed through a rating curve or table. The rating curve is constructed by plotting instantaneous flow measurements against corresponding stage heights. Flow is predicted at stages that do not have corresponding flow measurements by interpolating between higher and lower measured flows. If the rating curve does not cover the full range of the recorded stages, the curve is extended to two times the highest measured flow or one-half of the lowest measured flow. Flows predicted above or below the highest or lowest measured flows, but within two times the highest or one-half of the lowest measured flows, are qualified in all reports as such. Any extension of the curves beyond these limits are only used to estimate flow and the corresponding flow predictions are qualified to signify the values are an estimate.

Rating Extensions

In most cases, attempts are made to synthesize or model flows beyond measured flows. Estimates of flow at high stages are produced by linear regression. Average velocities measured at a site are regressed against the corresponding stages to estimate the average velocity of the unknown discharge. The average velocities are used with the cross sectional area derived from the Hydstra® database to estimate flows at high stages.

Another method available to model flows exceeding the rating curve involves the use of Manning's equation. This method requires longitudinal and cross sectional surveys of the channel to determine hydraulic slope, cross sectional area, and hydraulic radius. Site-specific Manning's n should be determined from previous measurements and regressed to provide a calculated estimate of n at the stage of the unknown flow. With these parameters Q (flow) can be solved.

Manning's Equation

$$Q = (1.486/n)AR^{2/3} S^{1/2}$$

Where:
Q = Flow
n = Manning Roughness coefficient
A= Cross sectional area
R = Hydraulic radius
S= Hydraulic slope

Models are checked by applying equations produced by regressing velocities and Manning's n to measured flows and checking relative accuracy of regression predictions.

Senior Level Review

All hydrologic data produced by SHU is reviewed for quality, accuracy, completeness, and compliance with SHU procedures. These periodic reviews occur quarterly throughout the year. An annual review of each station's data is done at the end of each Water Year.

All data submitted for quarterly review is checked for proper editing and quality code assignments. Any anomalies in the data or unexplained relevant events are noted. Rating curves are checked to ensure they are as up to date as possible. Review notes are generated for each station and submitted to the principal investigator and the SHU manager. It is the responsibility of the principal investigator to respond to the review notes and make any necessary corrections.

Streamflow data collected at individual gaging stations are submitted for final review at the end of each Water Year. At this time, final corrections are made to the stage record and the stage-flow rating curve is examined and finalized. If flow measurements made during the Water Year would significantly change estimated portions of the prior Water Year's rating, then this rating is also re-examined and modified as necessary. Retroactive corrections to streamflow data are not done beyond the Water Year just prior to the one under review.

Upon completion of data entry into the SHU database and development of the final rating tables, the basin lead prints a "SHU Review Packet" and presents it to the senior reviewer. The review packet consists of notes on problems during the Water Year, hydrographs and records of staff readings, copies of the rating curve(s), and any modeling notes used to estimate flow at stages above (or below) those actually measured. This packet, along with the SHU database (data workbench and ratings workbench) is used in the review. Each flow measurement is reviewed for accuracy and to ensure protocols are followed.

Audits and Reports

One approach SHU uses to assure the data are comparable between field staff is by mandating the protocols that must be followed. However, differences in application of the protocols by different field staff and the use of different sampling equipment can make a difference in the comparability of collected data. Data collected from different staff using different equipment can be compared statistically to evaluate performance. Measurements collected by field staff that do not meet expected levels of performance are then examined further for procedural or equipment errors.

Streamflow data are based on field measurements. Data from field measurements cannot be evaluated for accuracy, since there is no field reference standard to measure against. Instrumentation is factory calibrated through the use of a tow tank in accordance with international standards. Precision and bias are the most relevant performance standard for streamflow measured in the field by different staff and equipment. Precision and bias of field methods are most often evaluated with side-by-side monitoring by field staff to characterize the measurement variability.

SHU conducts annual streamflow measurement performance audits of field measurement variability. The performance audit includes:

- Conduct annual side-by-side measurements of streamflow at a reference location among different SHU field staff and their assigned equipment. The annual side-by-side measurement effort will be conducted in early fall when the lowest flows of the year are expected since measurement variability is greater at low streamflow levels.

- Conduct an assessment of the temperature data collected by thermistors deployed at many of stations with the continuous flow instrumentation. At several locations, Ecology's Freshwater Monitoring Unit also deploys continuous temperature probes in the streambed and riparian area. Temperature data collected by both methods will be statistically compared.

- Compute statistics of the measurement precision and bias of the side-by-side streamflow and temperature measurements collected and produce an annual audit report.

- Further examine procedures and equipment for errors or malfunctions for data sets that have the worst precision. There is no performance standard set for precision.

Bias will be inferred by the precision statistics of median scaled residual (MSR). This statistic provides a relative estimate of whether a protocol produces values consistently higher or lower than a different protocol.

$$MSR = 100*(P_i - O_i)/(\text{mean } O)$$, where P_i = predictions and O_i = observations

Precision among staff will be expressed in 3 different statistics: (1) root mean square error, (2) relative error, and (3) median absolute deviation (Reckhow et al. 1986):

1. The root mean square error (RMSE) presents an estimate of the variation in the same units as the measurement (e.g. cfs):

   $RMSE = (\sum (P_i – O_i)^2/n)^{½}$, where P_i = predictions and O_i = observations

2. The relative error (% Error) presents this variation as a percentage of the measurement mean:

   % Error = standard deviation/(mean * $n^{½}$)

3. The median absolute deviation (MAD) describes the dispersion of results:

   MAD = Median of $\{|X_i – X_M|\}$, where X_M = median

Data Verification and Validation

Data Verification

Each discharge measurement is given an overall quality rating of either *poor*, *fair*, *good,* or *excellent*. Determining this rating consists of two steps. The first step is a quantitative evaluation of the physical properties of the channel, cross section, and flow characteristics. A computer program has been developed that quantifies the key physical attributes of the cross section as well as other parameters of the discharge measurement such as the number of individual depth and velocity measurements (cells) and the percentages of discharge in each measurement cell. This evaluation results in a preliminary rating of *excellent*, *good*, *fair,* or *poor*.

The second step of the rating is based on the post measurement velocity tests done in the field. A rating of *excellent* is given to tests that show less than two percent error in the velocity tests. Errors between two and five percent are assigned a rating of *good*. A rating of *fair* has an error between five and eight percent. Errors over eight percent receive a rating of *poor*.

The overall quality rating of the discharge measurement is reported as the lower of the two ratings from steps one and two. For example, if the cross section and flow characteristics rating is *fair* and the velocity comparison is *excellent*, then the overall rating of the discharge measurement would be *fair*, with a total error between +/- five and eight percent. This overall rating of the discharge measurement is then used to assign appropriate Hydron® Quality codes.

Individual flow calculations are not adjusted based on the amount (percentage) of error associated with the overall quality rating. Rather, the quality rating will determine the tolerance for adjustment of the rating curve for a particular stream. It will also allow for determination of the reliability of the rating curve or segment of the rating curve. Generally, the rating curve line should align closely with flow measurement with a high rating. The rating curve would have more variability around measurements that are rated lower.

For example, two discharge measurements are made near the same stage and both measurements are rated as *excellent* with an error of less than two percent. The flow predicted by the rating curve at that stage differs by less than one percent from that measured. Typically, one would be satisfied with this rating curve. However, two later measurements at similar stages are rated *fair* and the flows predicted by the rating curve differs by seven and eight percent respectively.

In this example, there is no need to adjust the rating curve for the two most recent measurements. Because there is a higher error associated with these measurements, the present rating curve falls within the error bounds of these lower quality measurements.

Conversely, if new measurements have a lower error and the rating curve passes near flow points with higher error, there is justification to move the rating curve toward the flow points with a higher quality rating. This is particularly justifiable if the movement of the rating curve remains within the error margins of the lesser rated flows.

Note that these methods do not account for channel changes that may affect the stage/flow relationship and warrant adjustment of a rating curve. The above methods address the quality of discharge measurements and serve as a tool to assess rating curves based solely on that quality.

Data Validation

Streamflow data collected at individual gaging stations are reviewed at the end of each Water Year. At this time, final corrections are made to the stage record and the stage-flow rating curve is examined and finalized. If flow measurements made during the Water Year would significantly change estimated portions of the prior Water Year's rating, then this rating is also re-examined and modified as necessary. Retroactive corrections to streamflow data are not done beyond the Water Year just prior to the one under review.

Upon completion of data entry into the SHU database and development of the final rating tables, the basin lead prints a "SHU Review Packet" and presents it to the senior reviewer. The review packet consists of hydrographs, records of staff readings, copies of the rating curve(s), and any modeling notes used to estimate flow at stages above (or below) those actually measured. Technical notes compiled for each station at the end of the Water Year discuss the quality of flow measurements made during the year and how these measurements influence the overall quality of the rating curve at a station. This information, along with the SHU database (Data Workbench and Ratings Workbench) is used in the review.

Review of the stage record is conducted using the Data Workbench in Hydstra®. The review includes the following:

- Examine the history notes and check that the data-logger drift corrections have been made.
- Check that data gaps have been adequately filled.
- Check that the proper "Quality Codes" are entered for "estimated data", "ice", "gaps", etc.
- Note the maximum and minimum stage for checking the total range of the stage/flow rating.

Review of the stage/flow rating curve is conducted using the Rating Workbench in Hydstra®. The review includes the following:

- Check the "Period List" to ensure there is at least one period for each Water Year.
- Check the "Table List" to ensure at least one new rating table (or copy of old table) is entered for each Water Year.
- Examine the rating curve(s) for reasonable shape.
- Check the "Table as Text" to ensure that the range of the rating matches the maximum and minimum values of the stage record.
- Check that the rating points have proper "Quality Codes".
- Ensure that there is a reasonable explanation (or model) of any estimated flow values used to extend the rating beyond the actual measured points.

If errors are found during the review, the review packet is returned to the basin lead for correction, and the above procedures are repeated where necessary. When the review is complete, the date of the review and the initials of the reviewer are noted on the review packet.

The packet is then filed in the SHU library as part of the “Quality Assurance” record. The reviewer than notifies the SHU database administrator that the station has been reviewed and the data can be coded as “Reviewed”.

Data Quality Assessment

The data quality assessment process determines whether monitoring questions can be answered and the necessary decisions made, with the desired confidence. The data quality assessment evaluates the usability of the data and describes the graphical and statistical tools that are used to determine if the monitoring objectives have been met. Streamflow measurements that have met specified MQOs and passed data validations are presented on the SHU website. At this time, no further statistical analyses are reported by SHU from these data.

SHU collects streamflow information for use by numerous clients. Each of these clients conducts their own data quality assessment of the data to serve their particular objectives. Each client determines how the data are to be analyzed, which conclusions can be drawn from the data, and how the information is reported for their needs. Most of Ecology's current streamflow stations were located to serve the following six general purposes:

1. Ambient Monitoring Program - Ecology maintains rating curves and collects periodic stage heights for instantaneous streamflow data at stations routinely monitored for water quality.

2. Basin Stations - These sites were selected by the Watershed Lead Entities developing locally-based watershed plans under the Watershed Management Act (i.e., RCW 90.82 and ESHB 2514) to support establishment of instream flow rules.

3. Cooperative Stations - These sites were selected to meet the requirements of specific projects conducted with local cooperators that include the Suncadia Water Trust (Upper Yakima Basin), Comprehensive Irrigation District Management Plan (Dungeness River Basin), and the Forest Practices Board Cooperative Monitoring Evaluation and Research Committee (Willapa Bay Region).

4. Salmon Recovery Stations - These sites were selected by the Salmon Recovery Funding Board to support the Intensively Monitored Watershed Program.

5. Total Maximum Daily Load Stations - These sites were selected by EAP staff to support water quality modeling in establishing Total Maximum Daily Loads (TMDLs).

6. Water Acquisition Program Stations - These sites were established on select streams in the Naches River Basin (WRIA 38) and the Walla Walla River Basin (WRIA 32). These stations were installed above and below stream segments with potentially productive fish habitat areas, and water right holders with active diversions.

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