HJ Andrews Experimental Forest

Rating Curves and Flow Calculations for Gaged Watersheds

Contents:

Background information on rating curves:

Nine watersheds within the H.J. Andrews Experimental Forest (HJA) are gaged to measure streamflow using stream height or stage. The stage heights are converted to stream discharge by applying station specific discharge rating curves. The flumes and weirs used to measure and record stream stage have changed through the years, necessitating new rating curves for every change (flume, v-notch, fish ladder).

Manufactured flumes come with their own rating curves. These are built using assumptions that cannot always be met in field setups. Concrete flumes are also used at the HJ Andrews stream gages and these require site specific stage-discharge measurements across a range of flows to develop rating curves. Instrumentation used to record stage height has also changed over time at HJ Andrews Experimental Forest (see Watershed Description document for more information).

Typically, a rating curve follows a power-law relationship between stage height and discharge. This relationship is linearized by log transforming both stage height and discharge and using a simple linear regression, or a piece-wise simple linear regression that each operate over a specified water depth (also called stage height) interval. The power-law for of the equation and its log transformed version are shown below:

$$Y = a\ b^x \quad \text{or} \quad \ln y = \ln a + b \ln x$$

(where y= flow as cfs and x = stage height in ft.

Each rating curve is customized for the specific weir by fitting the curve to a set of calibration points. Calibration points are collected to build a relationship between stage height (either measured using a floating hook gage in a stilling well or directly measured with a ruler in the flume) and stream discharge (calculated from velocity measurements times known areas, dye dilution, or through volumetric measurement).

The accuracy and precision in the measurement of stage height and streamflow vary with type of instrumentation and flume or weir. Stage heights have estimated errors of 0.005 ft and this can vary with stage height and flow (Rothacher and Miner 1966). Accuracy is also influenced by hook gage or tape reference height measurement variations. Rapidly fluctuating water levels and observer bias can cause additional variations up to +/- .003 feet. The rating curves are constructed with as many observations of stage height and discharge as possible. Shifts in stream channels and flow paths occur over time, which make it challenging to apply consistent rating curves. In addition, we do not have good measures of accuracy and uncertainty for the various types of discharge measurements that have been used in our rating curves. Prior to 1997, the calibration points for rating curves were collected with variable methods, some of which were very coarse. Discharge accuracy is likely 10% of flow prior to 1997 (see section below on 2018 updates of rating curves) and 5-10% of flow post 1997.

HJA Gaged Watersheds, Rating Curve Summary

WS	Eqn. Set	Water Years	Description	Status
1	A	1953-1956	Original trapezoidal flume (18" floor) - Damaged and replaced in 1956	Rating curve based on a rating table developed from flume measurement calibration points with velocity-head rod method
1	B	1956-1999	Rebuilt trapezoidal flume (9" floor)	A new curve fit to these new calibration check points show a distinct change in the curve equations
1	C	1999-Present (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good. Continue to monitor
1	D	Oct 1999- Present	Rebuilt trapezoidal flume (9" floor)	Curve used to rerun WS1 streamflow data beginning WY1999
2	A	1953-Present (pending replacement beginning WY1999)	Trapezoidal flume	A new curve fit to these new calibration check points show differences from original curve at the low end. Early years (~1953- 1956) could be rerun based on early rating table since there are only flume-based stage measurements and no hookgage
2	B	1999-Present (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks marginal. Continue to monitor
2	C	Oct 1999- Present	Trapezoidal flume	Curve used to rerun WS2 streamflow data beginning WY1999
3	A	1953-1999	Trapezoidal flume	A new curve fit to these new calibration check points show differences from original curve at the low end. Early years (~1953- 1956) could be rerun based on early rating table since there are only flume-based stage measurements and no hookgage
3	B	Post-1964 flood until September 1966	Same flume with only flume measurements and no hook gage measures	Curve is based on flume measurements – used because no hook gage
3	C	1999-2022 (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good.
3	D	Oct 1999- Present	Trapezoidal flume	Curve used to rerun WS3 streamflow data beginning WY1999. Continue to monitor
6	A	1964-1997	Factory H-flume	Manufacturer's equation used - Overlay of check points on this curve indicates that low discharges may be overestimated
6	B	1998-Present	Trapezoidal flume	Curve based on velocity meter sampling points looks good.

6	C	1998-2022 (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good.
7	A	1964-1997	Factory H-flume	Manufacturer's equation used - Overlay of check points on this curve indicates that high and low discharges may be overestimated
7	B	1998-Present	Trapezoidal flume	Curve based on velocity meter sampling points looks good. Continue to monitor
7	C	1998-2022 (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good. Continue to monitor
8	A	1964-1987	Factory H-flume	Manufacturer's equation used – no calibration points available to check
8	B	1988-2018 no longer used-replaced w/ Set D	Trapezoidal flume	Curve based on velocity meter sampling points are generally ok, but revised the curve to include newer set of calibration points.
8	C	1997-2022 (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good. Continue to monitor.
8	D	1988- Present	Trapezoidal flume	Curve is based on all 71 calibration points. Improves low end but increases flow in mid-section of curve
9	A	1969-1973	Factory H-flume	Manufacturer's equation used – no calibration points available to check
9	B	1973-1979 (summers only)	Trapezoidal flume with v-notch (early style)	Curve based on volumetric sampling and calculated points is best guess
9	C	1973-Present	Trapezoidal flume	Curve based on dye-dilution and velocity meter sampling points looks good
9	D	1997-Present (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good. Continue to monitor
10	A	1969-1973	Factory H-flume	Manufacturer's equation used – no calibration points available to check
10	B	1973-1979 (summers only)	Trapezoidal flume with v-notch (early style)	Curve based on volumetric sampling and calculated points were best possible
10	C	1973-1996	Trapezoidal flume	Curve based on dye-dilution and velocity meter sampling points. A new rating segment was developed to better represent low flows
10	D	1997-2023 (summers only)	Trapezoidal flume with v-notch	Curve based on volumetric sampling points looks good. Continue to monitor
10	E	1997-Present	Trapezoidal flume	New curve was developed. Annual flows stay nearly identical with improvement at the very low end.
Mack Main	A	1980-Present	Trapezoidal flume	Curve based on velocity meter sampling points looks good. No new check points
Mack Fish	A	1996-2024	Compound weir: V-notch w/ rectangular section above	Curve based on volumetric sampling points and theoretical points (rectangular section) – no check points available for upper rectangular section

Rating equations associated with EQU_SET_CODES (HF004)

HJ Andrews Exp Forest hydrology data

SITE CODE	EQN_SET_ CODE	EQ_ SET	EQ_ VER	EQ_ NUM	MAX_HT (ft)	LN_A	B	C	D
GSWS01	1	A	1	1	0.020	1.654971	1.078052	0	0
GSWS01	1	A	1	2	0.076	3.458546	1.537138	0	0
GSWS01	1	A	1	3	0.274	2.887216	1.31555	0	0
GSWS01	1	A	1	4	2.000	3.359559	1.680522	0	0
GSWS01	2	B	1	1	0.041	3.481076	1.665892	0	0
GSWS01	2	B	1	2	0.085	1.767499	1.127728	0	0
GSWS01	2	B	1	3	0.113	3.464039	1.817153	0	0
GSWS01	2	B	1	4	0.186	2.440598	1.346943	0	0
GSWS01	2	B	1	5	0.342	3.465708	1.956849	0	0
GSWS01	2	B	1	6	0.701	3.056916	1.576129	0	0
GSWS01	2	B	1	7	2.000	3.21207	2.012922	0	0
GSWS01	3	C	1	1	1.000	1.606649	2.588479	0	0
GSWS01	67	D	1	1	0.045	4.390097	2.114193	0	0
GSWS01	67	D	1	2	0.186	2.426169	1.480041	0	0
GSWS01	67	D	1	3	2.000	3.10403	1.883403	0	0
GSWS01	72	E	1	1	0.035	4.511243	2.145515	0	0
GSWS01	72	E	1	2	0.063	3.35787	1.801527	0	0
GSWS01	72	E	1	3	0.166	2.288313	1.415004	0	0
GSWS01	72	E	1	4	0.350	3.021249	1.822914	0	0
GSWS01	72	E	1	5	2.000	3.126033	1.922719	0	0
GSWS01	73	F	1	1	1.000	1.428296	2.482232	0	0
GSWS02	4	A	1	1	0.200	2.366358	1.448769	0	0
GSWS02	4	A	1	2	0.352	3.318269	2.039951	0	0
GSWS02	4	A	1	3	0.610	2.851987	1.593208	0	0
GSWS02	4	A	1	4	3.000	3.041827	1.977656	0	0
GSWS02	5	B	1	1	1.000	1.512245	2.504343	0	0
GSWS02	68	C	1	1	0.031	1.478613	1.148933	0	0
GSWS02	68	C	1	2	0.159	2.144829	1.340027	0	0
GSWS02	68	C	1	3	3.000	3.060623	1.837247	0	0
GSWS02	74	D	1	1	1.000	1.395104	2.41783	0	0
GSWS03	6	A	1	1	0.069	2.577345	1.348321	0	0
GSWS03	6	A	1	2	0.143	1.799574	1.058093	0	0
GSWS03	6	A	1	3	0.321	2.711367	1.527144	0	0
GSWS03	6	A	1	4	3.000	3.042821	1.818537	0	0
GSWS03	7	B	1	1	0.298	2.426733	1.34033	0	0
GSWS03	7	B	1	2	3.000	3.103977	1.89932	0	0
GSWS03	8	C	1	1	1.000	1.48834	2.46917	0	0
GSWS03	69	D	1	1	0.031	0.392638	0.774904	0	0

GSWS03	69	D	1	2	0.104	1.857307	1.198288	0	0
GSWS03	69	D	1	3	0.260	2.888122	1.654642	0	0
GSWS03	69	D	1	4	3.000	3.130234	1.834356	0	0
GSWS06	9	A	1	1	0.218	0.373324	1.767373	0	0
GSWS06	9	A	1	2	0.460	0.660695	1.955948	0	0
GSWS06	9	A	1	3	1.006	0.800714	2.136444	0	0
GSWS06	9	A	1	4	2.000	0.799724	2.310509	0	0
GSWS06	10	B	1	1	2.500	1.272085	1.871948	0	0
GSWS06	11	C	1	1	1.000	1.263162	2.609228	0	0
GSWS07	12	A	1	1	0.218	0.373324	1.767373	0	0
GSWS07	12	A	1	2	0.460	0.660695	1.955948	0	0
GSWS07	12	A	1	3	1.006	0.800714	2.136444	0	0
GSWS07	12	A	1	4	2.500	0.799724	2.310509	0	0
GSWS07	13	B	1	1	2.500	1.428617	2.080909	0	0
GSWS07	14	C	1	1	1.000	0.808101	2.37987	0	0
GSWS08	15	A	1	1	0.218	0.373324	1.767373	0	0
GSWS08	15	A	1	2	0.460	0.660695	1.955948	0	0
GSWS08	15	A	1	3	1.006	0.800714	2.136444	0	0
GSWS08	15	A	1	4	2.500	0.799724	2.310509	0	0
GSWS08	16	B	1	1	2.000	1.304672	2.010448	0	0
GSWS08	17	B	2	1	0.235	1.020123	1.757868	0	0
GSWS08	17	B	2	2	0.760	1.303927	1.954112	0	0
GSWS08	17	B	2	3	2.000	1.456219	2.508602	0	0
GSWS08	18	C	1	1	1.000	0.912158	2.436042	0	0
GSWS08	70	D	1	1	0.027	1.983395	2.068395	0	0
GSWS08	70	D	1	2	0.115	1.400719	1.906961	0	0
GSWS08	70	D	1	3	0.690	1.221097	1.824042	0	0
GSWS08	70	D	1	4	2.000	1.472578	2.501527	0	0
GSWS09	19	A	1	1	0.218	0.373324	1.767373	0	0
GSWS09	19	A	1	2	0.460	0.660695	1.955948	0	0
GSWS09	19	A	1	3	1.006	0.800714	2.136444	0	0
GSWS09	19	A	1	4	2.500	0.799724	2.310509	0	0
GSWS09	20	B	1	1	2.500	0.493084	2.653538	0	0
GSWS09	21	B	2	1	2.500	-1.96422	0.966034	0	0
GSWS09	22	C	1	1	2.500	1.702991	1.936844	0.3470	0.058
GSWS09	23	C	2	1	0.004	-3.11429	0.435317	0	0
GSWS09	23	C	2	2	0.053	0.945934	1.174859	0	0
GSWS09	23	C	2	3	2.500	1.45447	1.347821	0	0
GSWS09	24	D	1	1	1.000	0.828001	2.412116	0	0
GSWS10	25	A	1	1	0.218	0.373324	1.767373	0	0
GSWS10	25	A	1	2	0.460	0.660695	1.955948	0	0
GSWS10	25	A	1	3	1.006	0.800714	2.136444	0	0

GSWS10	25	A	1	4	2.500	0.799724	2.310509	0	0
GSWS10	26	B	1	1	2.500	0.493084	2.653538	0	0
GSWS10	27	C	1	1	2.500	1.775749	1.929512	0.3025	0.051
GSWS10	28	C	2	1	0.033	3.187349	1.929556	0	0
GSWS10	28	C	2	2	2.500	1.63995	1.477808	0	0
GSWS10	29	D	1	1	1.000	0.782969	2.3769	0	0
GSWS10	71	E	1	1	0.010	-4.47709	0.241941	0	0
GSWS10	71	E	1	2	0.038	2.706364	1.803337	0	0
GSWS10	71	E	1	3	2.500	1.639965	1.47811	0	0
GSWSMA	30	A	1	1	0.555	3.5168	1.490794	0	0
GSWSMA	30	A	1	2	2.540	3.874576	2.098332	0	0
GSWSMA	31	A	2	1	0.162	1.197381	0.464005	0	0
GSWSMA	31	A	2	2	0.547	3.701232	1.839077	0	0
GSWSMA	31	A	2	3	2.540	3.871482	2.121452	0	0
GSWSMA	32	A	3	1	0.509	3.568	1.741562	0	0
GSWSMA	32	A	3	2	2.540	3.856196	2.168731	0	0
GSWSMA	35	A	4	1	0.509	3.568	1.741562	0	0
GSWSMA	35	A	4	2	2.540	3.856196	2.168731	0	0
GSWSMF	33	A	1	1	0.502	1.4884	2.449	0	0
GSWSMF	33	A	1	2	2.750	1.07848	1.853696	0	0
GSWSMF	34	A	2	1	0.810	1.555054	2.434724	0	0
GSWSMF	34	A	2	2	1.029	1.480674	2.081083	0	0
GSWSMF	34	A	2	3	2.750	1.492446	1.667571	0	0

Methods for collection of rating curve calibration points

Don Henshaw and Craig Creel 12/4/2002, revised 6/21/2018

Background:

Rating curve calibration points are taken at the small watershed stream gaging stations at the H. J. Andrews Experimental Forest. These calibration points are collections of stream stage height values with an associated discharge calculated for each point. Calibration points are used to build rating curves or check existing curves for each watershed. Rating curves translate stream stage height to discharge. Beginning in water year 1997 a program to systematically collect calibration points was initiated. Stream stage height, flume area and velocity measurements are used to calculate stream discharge for each calibration point.

Four methods for calculating discharge were used. The method selected was determined by several factors. These factors were:

> Flume/weir type, stream stage, number of velocity measurements taken, and location of measurements within the stream channel or flume.

U.S.G.S. Method:

The USGS method is a version of the current-meter method of measuring discharge as described in "Measurement and Computation of Streamflow: Volume1. Measurement of Stage and Discharge" (Rantz, S. E., Geological Survey Water-Supply Paper 2175, 1982, pg. 79 –183) for measurements of discharge in irregular shaped channels.

The width of the sampled stream cross-section is measured. Water depth, and velocity measurements are taken at measured intervals along the cross-section. Velocity measurements are taken at .6 of the water depth at each sample point using a top-setting wading rod and Model 200 Flo-Mate velocity meter.

Areas (Width X Depth) for each velocity measurement point are calculated by averaging the depths of the previous, current, and following sample points. The width is the sum of 1/2 the distance between the previous point and 1/2 the distance to the following point. Discharge (Velocity X Area) are calculated for each velocity sampling point and then summed to calculate total discharge for the stream.
This method was used when measurements were taken in irregular shaped sections of the stream channels, and measurements taken in "H" style flumes (WS's #6 & #7).

This method was altered for 4 points taken on the Mack Creek flume in 1994. In these cases, a velocity head rod was used instead of a velocity meter. 3 of these 4 points were later discarded and not used in the rating curve because the flow was deemed too high.

Area Method:

The Area method was developed to accurately calculate areas within stable/fixed form trapezoidal flumes. It takes advantage of known dimensions and angles of the flumes and very accurate measurements of depth from hookgages. (Note that areas are calculated somewhat differently at Mack Creek due to the uneven nature - flattening of the slope - of the flume construction. This variation of the method is the cumulative slope method and is described below.)

The width of the sampled stream cross-section is measured using a tape. Velocity measurements and depths were taken at measured intervals across the section using a top-setting wading rod and Model 200 Flo-Mate velocity meter. All velocity measurements were taken at 0.6 of the water depth.

Hookgage measurements were taken before and after the velocity measurements.
Areas are not calculated for each velocity sample point, but instead are calculated for 5 distinct zones within the flume trapezoid in which the sample points are located singly or as a group. Two of the zones are "edge" zones. These zones are the small triangular areas on each side of the flume in which the first and last sampling points occur. Velocities within these zones tend to be significantly lower than the other zones. The width of the edge zone is the distance from the edge of the water to the velocity sample point plus 1/2 the distance to the following or previous sample point. The depth is calculated by dividing the width of the zone by the tangent of the flume side slope angle from vertical. The area is then calculated using the area formula for triangles ([W x D] /2).

Two of the remaining three zones are "intermediate slope" (IS) zones. IS zones are the areas covering the sloped sides of the flume between the edge zones and the edge of the level or flat bottom portion of the flume. Area calculation for IS zones are a 3 step process. First a width for the entire triangular area from the edge of water to the edge of the level/flat bottom section of the flume is calculated by multiplying the starting hookgage measurement by the tangent of the flume side slope angle from vertical. Next, using the calculated width and starting hookgage measurement for depth, area is calculated using the triangle area formula. Finally the area of the adjacent edge zone is subtracted from the calculated area to arrive at the area for the IS zone.

The final zone or "center" zone is the rectangular area above the level/flat bottom portion of the flume. The known or documented width of the level/flat bottom is multiplied by the median hookgage depth to calculate the area of the center zone. Discharge for all zones are calculated by multiplying the area of the zone by the average of all velocity measurements taken within the zone. Discharges for each zone were summed to calculate total discharge thru the flume.

This method was used at sites with trapezoidal flumes with consistent side slope angles and known dimensions (WS's# 1, 2, 3, 6, 7, 8, 9 & 10), and an adequate distribution of velocity sampling points along the measurement cross-section.

Tangent angles used by site were:
30 degrees - WS# 6, 7, 8, 9 & 10
65 degrees - WS# 1, 2, & 3

Cumulative Slope Method:

The "Cumulative Slope" method is a version of the Area Method designed specifically for the trapezoidal flume at Mack Creek. Initial attempts to apply the Area method to the Mack Creek resulted in large differences between the measured and calculated cross-section widths. This indicated that the documented flume side slope angle was not correct. A precision survey of the sampled cross-section was done, and verified the documented angle was incorrect. The survey data showed that the side slope angle increased with increased distance away from the edge of the level/flat bottom of the flume.

Using the survey data a table of flume side slope angles for ranges of stream stage heights was developed to use in the Area Method of discharge calculations for Mack Creek. Each angle in the table is a mean of cumulative angles from both sides of the flume. Cumulative angles are defined as the calculated angle from measurements of cumulative change in elevation over a cumulative distance.

*Side slopes change greatly from cumulative angle trends in this range. Recommend calculating discharge for area below 2.472 using table values then calculating area above 2.472 using table values. Add the two to get total area.

Table of Cumulative Angles by Stage for Mack Creek

Stage Range	Horz. Angle	Vert. Angle (Area Method)
0.000 - 0.491 ft.	14.04 degrees	75.96 degrees
0.492 - 0.714	13.77	76.23
0.715 - 0.923	13.13	76.87
0.924 - 1.144	13.12	76.88
1.145 - 1.368	13.08	76.92
1.369 - 1.593	13.03	76.97
1.594 - 1.816	12.99	77.01
1.817 - 2.031	12.91	77.09
2.032 - 2.244	12.89	77.11
2.245 - 2.471	12.86	77.14
2.472 - 2.500	10.45*	79.55*

Average Method:

The "Average" method of discharge calculation is simply multiplying the average of all velocity measurements taken in the stream channel or flume by the total area of flow. This method was used when a good measure of area existed, but due to the location, configuration, or number of velocity measurements the alternative methods could not be used.

Velocities were taken at varied positions and depths using velocity meters mounted on a top-setting wading rod or hand held wand. Two Model 200 Flo-Mate velocity meters with top-setting wading rods were purchased and used beginning October 1996.

(Note that areas are calculated somewhat differently at Mack Creek due to the uneven nature - flattening of the slope - of the flume construction. This variation of the method is the cumulative slope method and is described under the AREA method.)

Bucket Method:

The “Bucket” method of discharge calculation is the process of measuring the time to fill a container of known volume. This is repeated 3 times. The times are then averaged and divided into the volume of the container to produce a per second discharge rate.

This method was used mostly during the low flow periods at sites where water depths did not allow use of a velocity meter, and had a physical configuration such that allowed for a good catch of the flow in a container. This method was also used at sites where v-notch weir plates were used, since attempts at using a velocity meter for measuring discharge provided inconsistent results when compared to the bucket method.

Difference Discharge Method:

The Difference Discharge method was used to develop a discharge rating curve for the fish ladder weir located at the Mack Creek gaging station where other methods of discharge measurement were not possible or provided inconsistent results.

The Difference Discharge method uses the change in discharge in the trapezoidal (main) flume of Mack Creek as the flow gate to the fish ladder is opened and adjusted as the discharge for the fish ladder.

The method begins with the flow gate to the fish ladder closed, so no water is entering the fish ladder weir. The stage of the (main) flume is recorded, and discharge calculated from existing equations for the main flume. The flow gate to the fish ladder is then opened, and after a period of flow stabilization the stage of the fish ladder and main flume are recorded. Using the existing equations the after opening discharge for the main flume is calculated, and subtracted from the before opening value. The difference in the before and after discharges in the main flume is recorded as the discharge for the fish ladder weir (use with after-opening stage of the fish ladder).

To check the accuracy of this method velocity measurements were taken in the main flume before and after opening the fish ladder gate. Discharges for the main flume were calculated using the cumulative slope method, and compared to the discharge values from the existing equations.

Calculation Method:

Extra rating points for the v-notch were derived when the v-notch is removed/replaced by calculating flow using the main flume rating equations immediately preceding/following configuration change with the preceding/following v-notch stage height.
This method was only used for the early v-notch weirs used on WS 9 and 10 during the 1970s.

Derived Method:

Extra rating points for the main flume were derived from v-notch bucket points taken directly before/after the v-notch is removed/installed by using main flume gage height immediately preceding/following configuration change. The assumption here is that the streamflow represented by the bucket sample point does not change before the gage height can be read from the regular flume after v-notch removal (or has not changed since the installation of the v-notch). Also, after v- notch removal we assume the regular flume gage height has stabilized before being measured.
This method is only used at sites where a v-notch weir is removed or installed on a regular basis.

Velocity Head-Rod Method

The velocity head-rod method was used in the 1950s on HJA WS 1, 2 and 3 to build rating tables for these watersheds. These rating tables related stream stage height based on direct flume measurement to the calculated discharge. Once hookgages were installed and adjusted, these rating tables were used to build rating curves based on stage height from the hookgages (See flume-hookgage method). The exception is the original flume at WS1 which was operative 1953-1956. This period is still represented by these original flume stage height-discharge points as there was no hookgage operative at this time.

The following excerpt on velocity-head rod measurements is from:
Wilm, H.G., & Storey, H.C., November 1944. Velocity-Head Rod Calibrated for Measuring Stream Flow, Civil Engineering, vol. 14 no. 11, page 475-476.

"A dependable yet cheap and rugged measuring stick was developed several years ago at the San Dimas Experimental Forest, in Southern California, to facilitate the calculation of discharges from mountain streams. This device, which has been described in technical publications, is particularly useful in gaging small volumes of flow containing varying amounts of bed-load and silt. Measurement of these flows is made continuously by weirs or measuring flumes, the calibration of which should occasionally be checked in place. The instrument is simple, portable, easy to construct and accurate within practical requirements. Its principle is not new, being simply an application of Bernoulli's theorem somewhat different from that employed in the Pitot tube.

In use, the rod is first placed in the water with its foot on the bottom and the sharp edge facing directly upstream. The stream depth at this point is indicated by the water elevation at the sharp edge, neglecting the slight ripple, or "bow wave." If the rod is now revolved 180 deg, so as to oppose the flat edge to the stream, a hydraulic jump will be formed by the obstruction to the flow of the stream. The average height of this jump measures the total energy content of the stream at this point; the jump height, minus the depth, equals the actual velocity head. Velocity can then be computed by the standard formula,

$$V = \sqrt{2gh} = 8.02\sqrt{h}$$

where, V = velocity, in ft. per sec
g = acceleration of gravity (taken as 32.16 feet per sec per sec)
h = velocity head, in ft.

The average discharge for the stream is obtained by taking a number of measurements of depth and velocity throughout its cross section. In tranquil flow, the jump on the rod is very steady and can be read easily; in turbulent flow, on the other hand, it often fluctuates as much as 0.1 ft. or even more. This fluctuation may be explained by the fact that the column of water impacting on the rod has constantly varying contents of kinetic energy. At one instant, filaments of water may converge upon the rod; at another they may diverge. As indicated by Eq. 1, however, errors in reading give errors in percentage of discharge equal only to one-half the percentage reading error.

For low discharge rates, the flume had already shown satisfactory correspondence with a V-notch weir; the rod data agree within practical limits of error for higher rates of flow.

The rod has obvious limitations; it is inaccurate for velocities much below 1 ft. per sec, and for streams with soft, unstable beds, and it cannot be handled well in streams moving faster than 8 or 9 ft. per sec. It has, however, a very definite and considerable value as the only method usable within this range, where the streams to be measured contain debris and bed-load."

Flume-Hookgage Method:

Velocity measurements were taken with a velocity-head rod in the early years at WS 1, 2, 3 (1953-1958) in association with a direct stage height measurement in the flume. Rating tables were developed based on these measurements (See velocity head-rod method). After new hook gages were installed and properly adjusted, simultaneous direct flume and hook gage measurements (1957-1964) were collected. The original rating tables based on the direct stage height measured in the flume were used to determine discharge. New calibration points were generated using the hookgage stage height reading and discharge determined through these original rating tables from the corresponding flume reading. These generated calibration points were used to fit the long-standing rating curves used at WS 1, 2 and 3. The rating curves were originally generated in 1966 but applied to the entire record.

Dye Dilution Method:

The dye dilution method was used by Dennis Harr on both watershed 9 and 10 in the 1970s. These data points are used today in building rating curves for these watershed main flumes. The following description is excerpted from a Harr white paper: Flume Calibration using the Dye Dilution:

The dye dilution technique may be used to calibrate stream gages such as the trapezoidal flumes at Watersheds 9 and 10. A dye solution -- in this case Rhodamine WT, a fluorescent dye -- of known concentration is injected at a constant rate upstream from the flume. The dilution of this dye solution is determined downstream after mixing of the dye has occurred. The two major pieces of equipment used in the dye dilution technique are a constant rate dye injection apparatus and a fluorometer.

Discharge is determined by: Q=((N1-N2)/(N2-N0))*(i/c) where

Q = discharge (ft /sec)
N1 = concentration of dye injected into the steam
N2 = concentration of dye after dilution by streamflow N0
= concentration of dye upstream from injection point i =
injection rate (ml/sec)
c = constant to convert ml/sec to ft./sec (28,320)

Rational for updating discharge data from small watersheds in 2018
HJ Andrews Experimental Forest

Don Henshaw, Sherri Johnson, Steve Wondzell 24 August 2018
Revised 23 October 2018

Rating curves are used to calculate stream discharge from stage height at stream gages in the HJ Andrews Experimental Forest. The Andrews Forest hydrology field team has been regularly collecting rating calibration points for the past 20+ years. Most of the points collected over these years have been at relatively low flow periods when v-notches are installed or removed, although a small collection of points have been taken at higher flows.

Previous updates include rating points collected from 1996 to 2002 that were used to improve rating curves for some watersheds (WS 8, 9, 10, Mack), or used to construct rating curves (WS 6, 7, v-notch weirs), or simply collected as a means to continually check and verify the accuracy of existing curves (WS 1, 2, 3, and 6&7 H-flumes). Since 2002, updates have not occurred to rating curves and calibration points have only been used to check the accuracy of existing rating curves.

Over the spring and summer of 2018, all of the rating curves have been evaluated with respect to these check calibration points. While most of the rating curves appear to match the new calibration points well, there are issues which require attention or further investigation. In particular, issues with the original rating curves and v-notch transitions for WS 1, 2, 3 had been observed but never previously addressed. Updates to WS 8 and WS 10 are also being considered. This document explains the planned process to update the rating curves and discharge data.
Rating curves for WS 6, 7, 9, Mack and for all WS when v-notches are on do not show a need for adjustment at this time but checking rating curves is a constant process. Because we have few recent calibration points at higher flows in a number of the watersheds, we need to systematically be collecting calibration points in the future.

This document describes proposed changes to rating curves based on field measurements and analyses of existing data. Other updates will need to occur, including the precision of the discharge data based on the accuracy and repeatability of field measurements and calculations of rating curves. However, we have not worked through that methodology for calculating magnitude and sources of error that change throughout the annual hydrologic cycle, and how to display the changes in precision in the database.

Background information on rating curves:
A rating curve is developed for every weir (flume, v-notch, fish ladder) within the Andrews Forest. Typically a rating curve follows a power-law relationship between stage height and discharge. This relationship is linearized by log transforming both stage height and discharge and using a simple linear regression, or a piece-wise simple linear regression that each operate over a specified water depth (also called stage height) interval. The power-law for of the equation and its log transformed version are shown below:

$$Y = a\, b^{x} \quad \text{or} \quad \ln y = \ln a + b \ln x$$

(where y= flow as cfs and x = stage height in ft.)

Each rating curve is customized for the specific weir by fitting the curve to a set of calibration points. Calibration points are collected to build a relationship between stage height (either measured using a floating hook gage in a stilling well or directly measured with a ruler in the flume) and stream discharge (calculated from velocity measurements times known areas, dye dilution, or through volumetric measurement).

WS 1, 2, 3 main flume rating curves:
Early calculations of discharge at WS 1, 2, 3 (1953-1958) were made using velocity measurements taken with a velocity-head rod multiplied times area of that measurement. Stage height measurements were also collected in the flume. Tables of rating curves were developed based on these measurement of discharge and stage height. After original hook gages were installed and properly adjusted, simultaneous flume and hook gage measurements (1957-1964) were used to generate calibration points using the hook gage- stage height reading and discharge determined through these original rating tables from the corresponding flume reading. These measured calibration points served as input for calculating the original rating curves (~1966) and have continued to be used (through WY 2017) at WS 1, 2 and 3.

Differences between new measurements and original rating curves can occur for several reasons: updated methods for measuring velocity and discharge are more precise compared to velocity- head rod, general settling of the weir that either changed the slope of the weir channel or its elevation relative to the hook gage, a change in roughness of the weir, or changes in shape of the stream channel and/or roughness of the upstream channel, streambed, and banks that change location and amplitude of the standing waves that have been observed within the flumes.

Issues for WS 1, WS 2 and WS 3:
WS 2: Calibration points have been collected WY 1996 to 2017. A new rating curve fit to these new calibration points show differences from original curve at lower stage heights and discharge. The new rating curve that includes these updated points shows that total annual yield would decrease by about 2%. Discharge calculated using new calibration points and rating curve will show less abrupt shifts when v-notch is installed or removed.

WS 3: Calibration points have been taken WY 1996 to 2017. A rating curve fit to these more recent calibration check points shows that discharge is comparatively lower or higher in separate sections in the lower portion of the curve. Overall, total annual yield would decrease by approximately 3% using the new curves.

WS 1: Calibration points were collected WY 1996 to 2017 and have been used to rebuild the rating curve for WS 1. This new rating curve shows a distinct change in discharge from the original rating equations. Initial calculations using the new curves show that total annual yield is 18 to 24% less than previous total annual yield estimated using the current (original) rating curves. The new equations also provide more consistent discharge values during transitions of putting on and taking off the v-notch weir. V-notch rating curves were developed since the initiation of v-notch measurements (1998). Updated rating curves will help smooth (but not entirely remove) shifts in calculated discharge that occur on v-notch installation/removal.

Proposed plans for updating discharge data at WS 1, 2, 3:
Recalculate discharge from these three watersheds using the new rating curves. For WS 2 and WS 3, replace existing data beginning with WY 1999 through WY 2016, and continue forward using these new curves. Save and provide the existing discharge data (WY 1999 – WY 2016) online as a separate entity in HF004. [For WS 1, recalculate discharge for the period from WY 1962 to the end of WY 2016 with the new curves and continue forward with these new curves. Note: WS1 was only replaced from WY 1999 through WY 2016]. Save and provide previous discharge data at 5-minute resolution and place these data online as a separate entity in HF004.

Rationale:
Calibration points taken from 1998 to 2017 appear to be internally consistent over this period. The v-notches in these small watersheds were first installed during summer of WY 1999.
Recalculation of discharge using new rating curves beginning in WY 1999 will provide consistency from this point forward. Rerunning data through the new curve beginning in WY 1999 would create a closer association of the main flume and v-notch rating curves, as both sets of rating points have been collected within the same time interval. The gaging station at WS3 was destroyed in the February 1996 flood and was rebuilt and a new hook gage installed in September 1998. V-notches were installed at all three of these watersheds in the summer of 1999. Rerunning these data beginning in WY 1999 would directly follow these significant changes. Additionally, the discharge jump caused when the v-notch is installed and replaced each year will be improved in most years.

There is a significant mismatch in WS 1 between current rating points and the original rating curve. There is evidence that 30% of this change (the difference in discharge from the original equation to the new equation) occurred around 1998. Calibration points appear to be consistent (linear regression on log-transformed data) since 1998. However, rerunning calculations of discharge beginning in WY 1999 (October 1998) will lead to a major shift in discharge starting 1998.

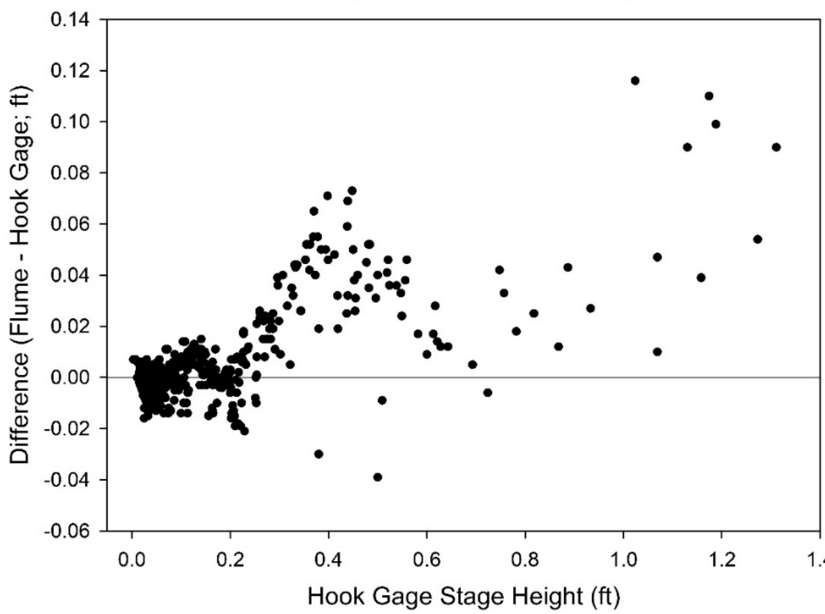
WS01 Gage: The Search for What Went Wrong Between 1962 and 1999

On each check date, water levels in the gage are recorded – in two ways. Five measurements of the water level in the flume are taken using a ruler. These 5 measurements are averaged to give the observed depth of water in the flume. Then, the water level in the stilling well is recorded from observing the hook gage. The hook gage was originally calibrated to the flume, and surveyed from a fixed bench mark. The hook gage and bench mark are surveyed annually. If they drift, then the hook gage is reset to the bench mark and the stage heights collected over the time interval from the current survey check to the previous check are corrected using a linear interpolation (i.e., assuming that the hook gage slowly and consistently drifted out of calibration over the course of the entire period). The original calibration and these annual surveys should keep the two measurements – ruler in the flume versus hook gage – closely aligned. That is, the relationship between the hook gage and flume should be stationary.

We can use that relationship to test whether there has been unaccounted drift in either the elevation of the flume or the hook gage. Changes in this relationship would appear as a consistent bias in the measured stage height.

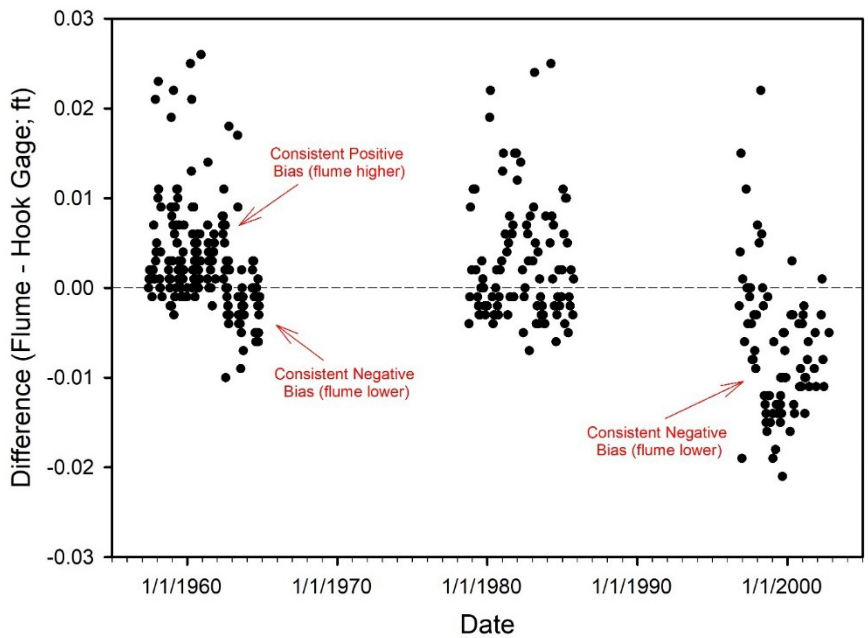
Note also that the relationship between the flume and hook gage appears biased at high discharge, with the water level measured with a ruler in the flume substantially higher than the measurement using the hook gage (Figure 1). This is not surprising. At high velocities, the water “piles up” along the leading edge of any obstruction, including a ruler.

Figure 1: Relationship between the accuracy of the water depth measured in the flume (expressed as the difference between the flume depth and the hook gage) versus stage height in the flume.
Note – measurements made with the V-notch weirs in place have been removed.



Because of bias at higher flows, to test the possibility of a drift in the elevations of the flume versus the hook gage, we only want to examine the low flow data. Using the lower flow data (excluding all points with stage height > 0.300 ft), we then look to see how well the flume and hook gage measurements agree (Figure 2).

Figure 2: The relationship between the water depth in the flume versus the water level measured from the hook gage in the stilling well adjacent to the flume.



While these flume and hook gage measurements have been made at each watershed check (at least every 3 weeks) for the duration of the record, we have only transcribed data from the field check forms for three periods shown above: A) 1957-1964, B) 1978-1985, and C) 1996-2002.

Also note that any measurements made at high flow (i.e., stage height measured off the hook gage > 0.300 ft) have been deleted from this analysis.

- Even though the high discharge data have been removed (stage height > 0.300 ft), there are still several points when the flume measurement with the ruler was 0.010 to 0.030 ft higher than the hook gage. We suspect that there are "erroneous" readings.
- We should expect the errors to be small and somewhat evenly distributed above and below the zero line – as is seen in the middle cluster of points collected form the mid- 1970s through the late 1980s. Further, the overall relationship should not change over time. So, while the data points collected between 1978 and 1985 are not perfectly evenly distributed, the general pattern and presence of high outliers should be consistent over time. That does not appear to be the case.
- The points collected in the 1950s and 1960s show two strange biases with the flume measurement consistently higher than the hook gage until the beginning of WY1962, after which the flume tends to read lower than the hook gage.
- By the late 1990s through the late 2000s, we see that the flume was consistently lower than the hook

gage – and by a substantial amount (~0.010 feet) or 3 mm.

- Although a consistent bias of only 0.010 ft may seem like a very small amount, it is a substantial error when accounted for over the entire water year. Don Henshaw tested the influence of changing stage height by 0.010 ft and showed that an error of that magnitude would change total annual water yield by ~7%.
- We do not know why the flume and hook gage measurements should change and show a long-lasting bias. Some potential reasons:
    - The flume has settled over time, so while the hook gage and bench mark survey have been consistent, the calibration between the flume and hook gage has drifted. The data shown above seem to indicate that the change occurred rapidly, not from a slowly settling concrete slab. This explanation seems somewhat unlikely.
    - Settling of the bench mark. The bench mark is located on a concrete wing wall that rests on bedrock and prevents flow from bypassing the gage. The change in the flume – hook gage relationship does not appear to be consistent with a slowly settling concrete slab. This explanation seems somewhat unlikely.
    - Replacement of the hook gage after it was vandalized– during which time the survey to the bench mark was in error and that change has been fixed into the data.
    - Disturbance to the gage and flume, potentially including the flume, bench mark, and hook gage during a major flood.
    - An unspecified error made during the original or any of the annual survey checks on the gage.

Other Watersheds

WS 8: The H flume was replaced by trapezoidal flume in Oct 1987 (WY 1988) and a new hookgage installed. Twenty seven calibration points taken with a velocity meter and bucket points 1990-1996 were used to build the current rating curve. Checks made by plotting new calibration points on this rating curve are in general agreement, but the fuller set of rating points (1990-2017) shows improvement. An additional 44 points between 1997-2017 have been collected. These are a combination of low flow measurements with bucket catch and at higher flows, discharge calculated using velocity (from velocity meter) times area. When 71 points are used to build a new rating curve, there is a slight increase in in discharge, primarily at stage heights ranging from 0.25 to 0.40 ft. The new curve tends to increase total annual yield by ~3- 4%.

Proposed plan for discharge data from WS 8 main flume: Rerun all data using the new rating curve beginning with WY 1988 through WY 2016, and continue forward using the new curve.
Save and place the existing data (WY 1988 – WY 2016) online as a separate entity in HF004.

Rationale: The new curve uses more than double the number of calibration points than the original curve and improves the fit at the low end of the curve. All of the points from 1989 seem consistent overall and makes rerunning all of the data since this flume was constructed in 1988 the cleanest solution.
Caveat: There is still some uncertainty in the curve, particularly at stage heights ranging from 0.25 to 0.40 ft. range. This is likely the range contributing to the increases in calculated discharge. Collection of more rating points within this range would be desirable.

WS 10: 76 points based on the dye dilution points (collected 1975-1977) and velocity meter and bucket calibration points (collected 1996-2002) were used to build the rating curve. 28 additional check points match very well with the existing curve except at very low stage heights (<0.015 ft.). However, several new calibration points have been collected in this low range in recent years where none were available prior to 2002. The new curve uses the same equations as the original curve at stage heights above 0.037 ft.; Only the very low end range of calculated discharge will be changed. This has nearly no effect on total annual yield.

Proposed plan for discharge data from WS 10 main flume: Recalculate discharge using the new rating curve beginning with WY 1997 through WY 2016, and continue forward using the new curve. Save and place the existing data (WY 1997 – WY 2016) online as a separate entity in HF004.

Rationale: The new curve takes advantage of 28 additional calibration points taken at low levels to improve the low end fit of the curve. Recalculating discharge beginning in 1997 matches the year of the v-notch installation and will improve the transition from the main flume to v-notch rating curves. High flow discharge calculations will be unchanged.

Streamflow calculation and rating curve summary

Don Henshaw Status notes below are as of 31 May 2018 *Previous revision 24 April 2006*

Steps involved in transforming raw streamflow data into discharge data

A. Raw stage height data
   1. Historically, raw data were collected from Stevens A-35 recording charts or from Fischer-Porter punched tapes (See weir history). Raw data was digitized or otherwise condensed to keep only "key (turning) points", that is, points where the slope or trajectory of streamflow height changes. Each day's midnight point reading was also kept. A critical aspect of this approach is that this raw stage data points were spaced irregularly in time, and there were more points for periods of more rapid change such as during storms or during wet periods.
   2. Data collection was moved to data loggers. Originally, this same type of algorithm was used briefly in the Campbell Scientific programs. However, the algorithm, which set a tolerance for slope change before outputting a new point, was found to be missing subtle diurnal behavior in v-notch readings on WS 2&3. In WY 2002 the Campbell logger algorithm was changed to check data every 5 minutes and points were output if *any* change of stage was detected. In WY 2012 all data loggers were reprogrammed to output data every 5 minutes.

B. All raw stage height data are corrected in processing.
   1. All values are linearly adjusted through time to be consistent with reference observations of stage measured at hook gages (or tape at Mack Creek) located adjacent to each gage house.
   2. Historically, when hook gages are not installed, direct measurement of gage height is made in the flume with a rule, and the raw data points are adjusted to these flume readings.
   3. Outlier data points are removed and missing data segments are estimated from paired gage data.

C. Stream discharge is calculated and summary data is created
   1. A rating curve is associated with all nine small watershed flumes. The rating curve converts stage height in feet to discharge in cubic feet per second.
   2. Summary output is generated for each data point and daily, monthly and annual summaries are also generated.
   3. Discharge data can be generated for any specific output interval (e.g., 15 minute, hourly, etc.), where points for the desired time interval are determined by interpolating between the key stage height points and the rating curves are applied. This process is handled interactively on the web-based FLOW program (first launched 18 Nov 2002).

Background on rating curves

A. A rating curve is developed for every weir (flume, v-notch, fish ladder) within the Andrews Forest

1. Typically a rating curve is a single log-linear equation or multiple piecewise log-linear equations that each operate over a specified water depth interval. The equation form is a power function:

   $Y = a\, b^{x}$ or $\ln y = \ln a + b \ln x$

   (where y= flow as cfs and x = stage height in ft.

2. Each rating curve is customized for the specific weir by fitting the curve to a set of calibration points. (See HF002, Entity 2 for the raw calibration point data)
   a. Calibration points are collected to relate a specific stage height (either measured using a hook gage in a stilling well, or directly measured with a rule in the flume) to a determined measure of stream discharge (typically, calculated from velocity, dye dilution, or through volumetric measurement).
   b. The concrete trapezoidal flumes in use today at all Andrews' gages including the v-notches installed in summer have required the development of these custom-fit rating equations.
   c. Some of the early flumes (e.g. pre-built H-flumes installed at WS 6,7,8,9,10) came with a manufacturer's rating curve, and few or no calibration points were ever collected and no rating curves were developed.

3. The methods and technology for taking calibration points, and hence, possibly, their accuracy and precision, has changed over time at the Andrews. Calibration points consist of synchronous measures of stage height and velocity.
   a. *WS 1, 2, 3 main flumes*: Velocity measurements were taken with a velocity-head rod in the early years at WS 1, 2, 3 (1953-1958) in association with a direct stage height measurement in the flume. Rating tables were developed based on these measurements. After new hook gages were installed and properly adjusted, simultaneous direct flume and hook gage measurements (1957-1964) were used to generate calibration points using the hook gage stage height reading and discharge determined through these original rating tables from the corresponding flume reading. These generated calibration points served as input for generating the rating curves (~1966) still in use today (2018) at WS 1, 2 and 3.
   b. *WS 9, 10 main flume*: The dye dilution method was used to develop the WS 9 & 10 main trapezoidal flume rating curves from 1975-1977. Additional points were added from 1996 to 2002 before these rating curves were rebuilt. Additional points were collected with a velocity meter and with volumetric samples.
   c. *WS 9, 10 v-notch 1973-1979*: Volumetric or "bucket" samples were also used to directly measure discharge from 1973 to 1977 for the v-notch weirs in place during summers 1973-1979. Additional points were calculated based on using the main trapezoidal flume equation with v-notch stage height directly before or after removal of the v-notch.
   d. *All watersheds*: Velocity measurements have been regularly taken with a velocity meter starting after the February 1996 flood. Velocity meter measurements were also made at WS 8 from 1990-1995. Volumetric or "bucket" samples have also been used to measure velocity for the calibration of the v-notch weirs beginning in 1997.

4. Rating tables and rating curve equations
    a. In the late 1950s and early 1960s (prior to computerized statistical packages), stage height-discharge relationships were fitted by eye and rating tables were developed (WS 1, 2, 3).
    b. Subsequently curves have been fitted using regression techniques, typically with a log-linear or piecewise log-linear function. Piecewise functions have been used to account for bends in an otherwise straight log-linear relationship inferred from the calibration points; some rating curves have as many as seven equation segments (e.g., WS1).
    c. Other functional forms have been used (e.g., a reverse sigmoidal (cubic) curve for the main flumes at WS 9 and 10 in the 1970s)
    d. Rating curves for all Andrews flumes are now in log-linear or piecewise log-linear functional form (since Dec 2002).
    e. The USGS- maintained Lookout Creek gauge has no weir control structure and is still calibrated with annual surveys of cross-sectional channel area and velocity. Rating tables are modified as needed and stream discharge is calculated by the USGS. In 2012 the USGS selected AQUARIUS software by Aquatic Informatics to optimize workflows, consistency and data quality.

Summary of history and status of rating curves (WY2018) by gage

Watersheds 1, 2 and 3

A. Original rating curves:
    1. Rating tables for these basins were developed based on velocity-head rod measurements and stage height measured directly in the flume taken 1953-1958.
    2. Rating curve equations were developed for use with hook gage measurements in 1966 by PNW-Portland (Dorothy Martin, Sue Skinner, Floyd Johnson). In building these rating curves, rating points were generated using coinciding stage height measurements, both direct measurement in the flume and hook gage readings, in conjunction with the original rating table discharge based on the direct flume measurement. Approximate sets of calibrations points have been identified that were used to build these original equations.
    3. Note: WY 1953 to WY 1959 data was originally hand digitized with a minimum sketching of streamflow trace, and only daily discharge was calculated. These data charts were later electronically digitized and the discharge recalculated at a finer resolution. Caveat: There was no hookgage for most of these early years ~1953-1957 with only a flume measurement. While the recalculation of discharge would be most accurate using the original rating tables for WS 2 and 3, these watersheds were rerun and calculated using the rating curve developed based upon the hookgage. WS1 is not really affected because this original rating table was used from 1952 to 1956.

B. WS1, Equation Set A, version 1 (Oct 1952 - Aug 1956)
    1. Original flume (18” bottom) for WS 1 was operative for WY 1953 to WY1956 and was rebuilt in August 1956 after leaks were detected earlier that year. The curve built to calculate discharge for WS 1 was based on the early rating table derived from direct flume measurements and velocity-head rod rating points taken 1953-1956. There was no hook gage installed at this time. A rating table had been developed from a hand drawn curve through these velocity-head rod rating points. The rating curve currently used was created in 1988 based on this rating table.

2. **Status:** Checks made by plotting original rating points on this rating curve appear good. The curve was developed using summarized points from the rating table. The curve could be refit directly from the exact set of calibration points, but this seems unnecessary.

C. WS1, Equation Set B (Sep 1956 – Present, except summers beginning WY1999)
   1. This rating curve is as described in III.A.1., developed in 1966 for the main flume
   2. Check calibration points have been taken WY 1996 to Present
   3. **Status:** A new curve fit to these new calibration check points show a distinct change in the curve equations. Initial checks of a new curve show that annual streamflow seems to drop by about 18%. Checks of the hook gage – flume relationship using a double mass plot indicate changes in 1962 and again after replacement of the hook gage in 1998.

D. WS1, Equation Set C (WY 1999 – Present, summers only)
   1. V-notch weir has been in place every summer since July, 1999
   2. Rating curves are based on volumetric samples taken from Oct 1999 to Oct 2001. The "bucket" collection method has been used consistently but the method and efficiency was improved after the 1999 summer. The 1999 points have not been used in the final rating equation.
   3. Check calibration points have been taken from WY 2002 – Present
   4. **Status:** Checks made by plotting new calibration points on this rating curve appear good. Continue collection of check points.

E. WS1, Equation Set D (WY 1999 – Present, pending)
   1. Calibration points taken 1996-2017 have been used to rebuild the original rating curve WS1 Equation Set B.
   2. These calibration points will correspond better with the v-notch calibration points with both sets being taken after 1996, and all but a few taken after replacement of the hook gage in 1998.
   3. **Status:** Curve will be used to rerun the historic WS1 streamflow data beginning in WY1999 to Present, where WY1999 is the year the v-notch is installed. There is still uncertainty in the reason why the curve deviates so much from the earlier curve, or why the hook gage measurements appear to have increased versus corresponding flume depth measurements made with a rule in the flume.

F. WS2, Equation Set A (Oct 1952 – Present, except summers beginning WY1999)
   1. This curve is as described in III.A.1., developed in 1966
   2. Check calibration points have been taken WY 1996 to Present
   3. **Status:** A new curve fit to these new calibration check points show differences from original curve at the low end. Initial checks of the new curve show that annual streamflow only seems to drop by about 2%.

G. WS2, Equation Set B (WY 1999 – Present, summers only)
   1. V-notch weir has been in place every summer since July, 1999
   2. Rating curves are based on volumetric samples taken from Oct 1999 to Oct 2001. The "bucket" collection method has been used consistently but the method and efficiency was improved after the 1999 summer. The 1999 points have not been used in the final rating equation.
   3. Check calibration points have been taken from WY 2002 – Present
   4. **Status:** Checks made by plotting new calibration points on this rating curve appear adequate. Continue collection of check points and monitor.

H. WS2, Equation Set C (WY 1999 – Present, pending)
   1. Calibration points taken 1996-2017 have been used to rebuild the original rating curve WS2 Equation Set A.
   2. These calibration points will correspond better with the v-notch calibration points

with both sets being taken after 1996.
3. **Status:** Curve will be used to rerun the historic WS2 streamflow data WY 1999 to Present, where WY1999 is the year the v-notch is installed.

I. WS3, Equation Set A (Oct 1952 – Present, except summers beginning WY1999)
   1. This curve is as described in III.A.1., developed in 1966
   2. Check calibration points have been taken WY 1996 to Present
   3. **Status:** A curve fit to these more recent calibration check points show streamflow that is comparatively lower and higher in separate sections in the lower portion of the curve with the annual change about 3%.

J. WS3, Equation Set B (Nov 1964 – Sep 1966)
   1. Watershed 3 had no hook gage data to correct the discharge data (step I.B. above) for this period. Post 1964 flood streamflow data are calculated with a rating curve built from the original rating table or original velocity-head rod data points collected WY1953-WY1958, and is based on flume (rather than hook gage) measurements. Note: there was also no hook gage after the 1996 flood, Oct 1996 to October 1998 (both hook gages were destroyed by the floods), but post-1996 streamflow data have been calculated with the original hook gage-based equations to date.
   2. An approximate set of points have been identified that were used to build this original rating table and subsequently rating curve equations.
   3. **Status:** This curve is based on direct flume height measurement and is only used post-1964 flood. The curve seems reasonable based on plots of the original, approximate calibration points onto this curve. The curve could be applied to post-1996 flood data but never was applied due to the uncertainty in using this original rating curve. This curve could also be applied to the early years (1953-1957) before a hookgage was established, but only the rating curve based on the hookgage has been applied to these years.

K. WS3, Equation Set C (WY 1999 – Present, summers only)
   1. V-notch weir has been in place every summer since July, 1999
   2. Rating curves are based on volumetric samples taken from Oct 1999 to Oct 2001. The "bucket" collection method has been used consistently but the method and efficiency was improved after the 1999 summer. The 1999 points have not been used in the final rating equation.
   3. Check calibration points have been taken from WY 2002 – Present
   4. **Status:** Checks made by plotting new calibration points on this rating curve appear good. Continue collection of check points and monitor.

L. WS3, Equation Set D (WY 1999 – Present, pending)
   1. Calibration points taken 1996-2017 have been used to rebuild the original rating curve WS3 Equation Set A.
   2. These calibration points will correspond better with the v-notch calibration points with both sets being taken after 1996.
   3. **Status:** Curve will be used to rerun the historic WS3 streamflow data WY 1999 to Present, where WY1999 is the year the v-notch is installed.

Watersheds 6, 7, and 8

M. Original flume rating curves
   f. These basins were originally instrumented with purchased H-flumes, and the accompanying manufacturer's rating curves were used without any attempt at

validation. The H-flume at Watershed 8 was replaced with a trapezoidal flume in 1988. During the 1990s questions about the accuracy of the H-flume rating curves led to calibration measurements being taken at Watersheds 6 and 7 in 1996-1997 prior to the removal of the H-flumes and their replacement with trapezoidal flumes in 1998.

   b. These original manufacturer rating curves used for the 1963-1997 periods can still be validated at Watersheds 6 (18 calibration points) and 7 (22 calibration points). Overlay of these points on the manufacturer's curve indicates that high and low discharges may be being overestimated at WS 6, and low discharges may be being underestimated at WS 7.

2. WS6 Equation Set A (Oct 1963 – Sep 1997)
   a. Manufacturer's rating equations were used. A custom rating curve was never developed.
   b. 18 calibration points were taken WY1996 and WY1997
   c. **Status:** It would be possible to develop a rating curve which could be used to rerun all or part of this streamflow data. Overlay of these points on the manufacturer's curve indicates that high and low discharges may be being overestimated at WS 6
3. WS6 Equation Set B (Oct 1997 – Present, except summers beginning WY1998)
   a. 22 calibration points taken with a velocity meter 1997-1999 have been used to build the rating curve
   b. Check calibration points have been taken from WY 2000 – Present
   c. **Status:** Checks made by plotting new calibration points on this rating curve appear good. An additional 33 points have been collected, mostly during low flow (<.15 ft.). Continue collection of check points.
4. WS6, Equation Set C (WY 1998 – Present, summers only)
   a. V-notch weir has been in place every summer since June, 1998
   b. Rating curves are based on volumetric samples taken from Jun 1998 to Oct 1999
   c. Check calibration points have been taken from WY 2000 – Present
   d. **Status:** Checks made by plotting new calibration points on this rating curve appear good although there are many more calibration points now. Continue collection of check points and monitor.
5. WS7 Equation Set A (Oct 1963 – Sep 1997)
   a. Manufacturer's rating equations were used. A custom rating curve was never developed.
   b. 22 calibration points were taken WY1996 and WY1997
   c. **Status:** It would be possible to develop a rating curve which could be used to rerun all or part of this streamflow data. Overlay of these points on the manufacturer's curve indicates that low discharges may be being underestimated at WS 7
6. WS7 Equation Set B (Oct 1997 – Present, except summers beginning WY1998)
   a. 19 calibration points taken with a velocity meter 1997-1999 have been used to build the rating curve
   b. Check calibration points have been taken from WY 2000 – Present
   c. **Status:** Checks made by plotting new calibration points on this rating curve appear good. An additional 35 points have been collected, mostly during low flow (<.16 ft.). Continue collection of check points.
7. WS7, Equation Set C (WY 1998 – Present, summers only)
   a. V-notch weir has been in place every summer since June, 1998
   b. Rating curves are based on volumetric samples taken from Jun 1998 to Oct 1999
   c. Check calibration points have been taken from WY 2000 – Present

d. **Status:** Checks made by plotting new calibration points on this rating curve appear good although there are many more calibration points now. Continue collection of check points and monitor.

8. WS8 Equation Set A (Oct 1963 – Sep 1987)
   a. Manufacturer's rating equations were used. A custom rating curve was never developed.
   b. **Status:** No calibration points were collected. Rating curve is static.
9. WS8 Equation Set B (Oct 1987 – Sep 2016, except summers beginning WY1998)
   a. Curve will be replaced with Equation Set D, and all data rerun beginning Oct 1987
   b. 27 calibration points taken with a velocity meter and bucket points 1990-1996 have been used to build the rating curve
   c. Calibration points taken Jan 1990 to Nov 1991 were used to fit the original version of this curve, which was a single equation curve. This curve was operative until Feb 1996 but replaced with version 2 and all data was rerun through the newer version 2.
   d. Check calibration points have been taken from WY 1997 – Present, plus an additional point from 1989
   e. **Status:** Checks made by plotting new calibration points on this rating curve are generally good but the curve could be improved at the very low end. An additional 47 points have been collected, a combination of low flow checks and velocity meter points at higher flows. A new rating curve is built from the full collection of points including the original 27 plus the additional 47 points to replace this curve.
10. WS8 Equation Set C (summers only, 1997 – Present)
    a. V-notch weir has been in place every summer since June, 1997
    b. Rating curves are based on volumetric samples taken from Jun 1997 to Oct 1999
    c. Check calibration points have been taken from WY 2000 – Present
    d. **Status:** Checks made by plotting new calibration points on this rating curve appear good although there are many more calibration points now. Continue collection of check points and monitor.
11. WS8 Equation Set D (Oct 1987 – Present, except summers beginning WY1998)
    a. The original 27 calibration points taken with a velocity meter and bucket points 1990-1996 and 47 additional points (WY 1997-2017) taken with a velocity meter, bucket, or derived from bucket collection through the v-notch flume have been used to rebuild the rating curve to replace Equation Set B. Three points were eliminated due to suspect collection conditions and outlier values – 71 points used.
    b. This curve will be used to rerun all data from WY1988 through WY 2016 and continue use with WY 2017.
    c. **Status:** The new curve tends to raise annual totals by 1.5 to 2 inches (~3-4%) with the new curve returning higher flow in the range of .3 to .7 cfs. More data points collected in the .25 to .40 ft. range would help to verify this curve. The low flow calibration points should improve the low end of the curve.

Watersheds 9 and 10

1. Original flume rating curves
   a. Similarly to WS 6, 7, and 8, these basins were originally instrumented with purchased H-flumes, and the accompanying manufacturer's rating curves were used without any attempt at validation from 1968 to August of 1973, when they were replaced with trapezoidal flumes.
   b. The rating curves for the trapezoidal flumes were originally based upon a reverse sigmoidal (cubic) curve, which were used until December 2002. The calibration points were collected with a dye dilution method and obtained between Nov 1975

and Dec 1977. Additional calibration points were obtained from 1996 to 1999, and the overlay of these points on the cubic rating curve indicated that low discharges in Watersheds 9 and 10 were being greatly underestimated, and apparently peak flows were over-estimated. Consequently, the rating curves for WS 9 and 10 were redeveloped in December 2002 and based on the dye dilution and velocity meter calibration points in log-linear form.

   c. V-notch weirs in Watersheds 9 and 10 were originally in place in summers 1973 to 1979. Calibration points were collected (volumetric samples) for the early v-notch at both watersheds. For unknown reasons, the rating curve developed for Watershed 10 was used for both Watershed 9 and 10, and the WS 9 calibration points were never used. In 2002, the original WS 9 volumetric sampling points were combined with derived points (based on calculated flows from the new regular flume equation at times when the v-notch was added or removed) and a new curve developed.

2. WS9 Equation Set A (Oct 1968 – Aug 1973)
   a. Manufacturer's rating equations were used. A custom rating curve was never developed.
   b. **Status:** No calibration points were collected. Rating curve is static.
3. WS9 Equation set B (summers only, 1973-1979)
   a. Original rating curve used the same equation as WS10 for this early v-notch, which was based on WS10 calibration points
   b. This rating curve was developed based on v-notch stage height after/before v-notch installation/removal and calculated discharge determined from corresponding main flume stage height (immediately before/after v-notch installation/removal) using rating equations (Equation Set C, version 2)
   c. Bucket points collected 1973-1977 were suspect and not used.
   d. **Status:** No additional calibration points are available. Rating curve is likely best guess possible.
4. WS9 Equation set C
   a. A reverse sigmoidal (cubic) curve with cubic and quadratic parameters was Version 1 and used until December 2002. Subsequently the curve was refit and all data was rerun through the Version 2 rating curve.
   b. Rating curve Version 2 was redeveloped in the standard log-linear form in December 2002 based on the dye dilution points (collected 1975-1977) and velocity meter and bucket calibration points (collected 1996-2002).
   c. **Status:** No additional calibration points are available. Rating curve is likely best guess possible
5. WS9 Equation set D
   a. A v-notch weir in Watershed 9 has been in place since 1997 with curve based on volumetric bucket samples taken from 1997 to 1999.
   b. Check bucket sample points have been collected from 2002 to 2017.
   c. **Status:** Checks made by plotting new calibration points on this rating curve appear good. Continue collection of check points and monitor.
6. WS10 Equation Set A (Oct 1968 – Aug 1973)
   a. Manufacturer's rating equations were used. A custom rating curve was never developed.
   b. **Status:** No calibration points were collected. Rating curve is static.
7. WS10 Equation set B (summers only, 1973-1979)
   a. This rating curve was based on a combination of bucket points and calculated points (collected 1973 to 1977). Calculated points were determined using v-notch stage

height after/before v-notch installation/removal and calculated discharge determined from corresponding main flume stage height (immediately before/after v-notch installation/removal) using rating equations (Equation Set C, version 2)

   b. Additional points were calculated using method described in C.7.a from original data in 2002, and these points were used as a check on this original equation.
   c. **Status:** No additional calibration points are available. Rating curve is good.

8. WS10 Equation set C
   a. A reverse sigmoidal (cubic) curve with cubic and quadratic parameters was Version 1 and used until December 2002. Subsequently the curve was refit and all data was rerun through the Version 2 rating curve.
   b. Rating curve Version 2 was redeveloped in the standard log-linear form in December 2002 based on the dye dilution points (collected 1975-1977) and velocity meter and bucket calibration points (collected 1996-2002).
   c. **Status:** Very low flow bucket calibration points collected 2003 to 2017 indicate that a new rating segment could be developed to better represent this very low flow. A new rating curve Set E
9. WS10 Equation set D
   a. A v-notch weir in Watershed 10 has been in place since 1997 with curve based on volumetric bucket samples taken from 1997 to 1999.
   b. Check bucket sample points have been collected from 2002 to 2017.
   c. **Status:** Checks made by plotting new calibration points on this rating curve appear good. Continue collection of check points and monitor.
10. WS10 Equation set E
   a. An additional 28 calibration points (bucket and derived points) were collected from 2002 to 2017 mostly at very low flow levels. These 28 points were added to 76 existing points used to build Eq Set C, ver.2 to build this curve.
   b. The annual total flows from this new curve are nearly identical to those from EQ. Set C as the high flow equation segment remains exactly the same. Only noted changes are at extremely low levels
   c. This curve is intended to replace the existing data from WY 1997-WY2016.
   d. **Status:** New curve is developed by adding 28 new low flow calibration points. Continue collection of check points and monitor.

Mack Creek

1. Mack Creek Equation set A
   a. Mack Creek was instrumented with a trapezoidal flume in 1980.
   b. Earlier versions of this rating curve were developed in 1994 and 2001. Data made available before 1994 had been run using a linear curve, which are considered invalid.
   c. At present, the discharge record is calculated from a piecewise log-linear rating curve, version 3, based upon 52 calibration points collected between 1983 and 2002.
   d. **Status:** Checks made by plotting new calibration points taken in 2002 and 2003 on this rating curve appear good. Continue collection of check points and monitor.
2. Mack Creek Fish Ladder Equation set A
   a. In 1996, when the Mack culvert was removed and replaced with a bridge, a fish ladder was added to the Mack Gage. The rating curve for the fish ladder’s compound weir (there is a rectangular cross-section above a v-notch) was originally derived using theoretical relationships.

b. Calibration points collected with the velocity meter and by differencing the flow change in the main flume when the fish ladder is opened/closed were never used in developing rating curves likely due to suspect accuracy of these points.
c. The fish ladder rating equations were recreated (version 2) in 2001. Additional rating bucket points taken in 2001 are used to fit equation 1, but theoretical curve equations are used to generate points for the upper stage levels within the rectangular section above 0.8 foot depth (equations 2 and 3).
d. **Status:** No check measurements have been made since this equation version was established. Should the fish ladder be consistently opened at higher flows, new calibration points should be captured to check the theoretical portion of the rating curve.

Lookout Creek

USGS maintains the Lookout Creek stream gage (14161500).

WY 1950 – WY 1955: USGS maintained A-35 charts (Stevens Type A stage recorder)
WY 1956 – WY 1963: USFS PNW maintained A-35 charts (Stevens Type A stage recorder)
WY 1964 – WY 1965: USGS maintained A-35 charts (Stevens Type A stage recorder)
WY 1966 – WY 1974: USGS maintained Fischer-Porter paper punch-tape stage recorder at 2-hour intervals
WY 1975 – WY 1986: USGS maintained Fischer-Porter paper punch-tape stage recorder at 1-hour intervals

Chart data was digitized using a Summagraphics 1812 Digitizer with a precision of .03 feet (1949-1965). Punch tape data stored on computer printouts was entered (1965-1986).

The Lookout Creek Stream Gage was maintained by the U.S. Forest Service PNW from WY 1956 through WY 1963, These data are not available through the USGS. Three separate calibrations (rating tables) were developed during the seven years. USGS requires that this be done every year, and does not acknowledge any data during the Forest Service maintained period. While the Forest Service was operating the gage from 1956-1963, only one stream calibration was made to create a rating table in 1961. The 1955 USGS rating table was used in 1956, but water years 1957 and early 1958 seem to not fit very well in either the 1955 or subsequent 1961 rating table, although the 1961 table was used and seems a better match. Water years 1958, 59, 60, and 62 were originally hand scanned and hourly data is only approximate, but all storm peak flow points are accurately noted.

All 24 USGS Lookout Creek rating tables used over the period of 1950-1986 by the USGS to generate stored daily values and seasonal peak flow were gathered and entered (HF002, entity 3: https://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=HF002). These table data were used as the basis for fitting 24 sets of rating equations that calculated flow in cubic feet per second (cfs) from gage height (stage) in feet on an hourly basis. Using this equation form allows the gage height to be linear interpolated on an hourly basis. This method is necessary for reducing the 16 years of digitized chart data, but was also used to linearly interpolate every hour when 2- hour interval punch tape data was collected (1966-1974).

As a means of checking the accuracy of the rating curves and digitization procedures, a new daily record is generated from the new rating curves and compared to the published USGS daily values. All of the new generated daily values fall within 5% of the USGS daily value when the flow in cfs is greater than 30, and fall with 8% of the USGS daily value when the flow is less than 30. Eighty-three percent of all new daily values fall within 3% of the USGS published values. Some differences between the newly constructed record and the USGS published values were likely caused by post-processing corrections or shifts in the original gage height data. Gage height data were adjusted accordingly to better match the USGS flow record for noted periods where a previous correction was evident.

An hourly record of Lookout Creek streamflow was reconstructed from WY 1950 (10-01-1949) through WY 1986 (09-30-1986). High resolution 30 minute data is currently available beginning WY 1987 and 15-minute resolution data beginning in WY 2010 though USGS. The WY1982 hourly data values are estimated from published USGS daily max-min values for this year.

Notes on the calculation of the volume of flow

Jinfan Duan November 28, 1994

DEFINITION:
Equation is a single relationship with fixed set of constants for certain range of stage heights
Break point is the maximum stage height where the defined equation can be used.
Rating curve is a set of equations that cover all possible stage heights.

ONE EQUATION VOLUME BETWEEN TWO POINTS

Assume between time t1 and t2, the stage height moves from h1 to h2 in a linear relationship and the equation

$$\ln(Q) = a + b\ln h + c(\ln h)^2 + d(\ln h)^3$$

can be used for any point within this time or stage domain, with a, b, c, d are fixed constants for this time. Then the total volume of water produced during this period is:

$$V = \int_{t1}^{t2} Qdt = \frac{1}{R}\int_{h1}^{h2} Qdh$$

with R = dh/dt = constant.

Several situations are considered:

1) R = 0

$$V = Q(t_2 - t_1)$$

2) Other
   1. C = d = 0;
      A) If b = -1,
         if either h_1 or h_2 is zero

$$V = (Q_1 + Q_2) * (t_2 - t_1) \; /2$$

         else

$$V = \frac{1}{R}\int_{h1}^{h2} Qdh = \frac{e^a}{R}\int_{h1}^{h2} \frac{1}{h} dh = \frac{e^a}{R}\ln\left(h / h_1 \right)$$

      B) Else

$$V = \frac{e^a}{R(b+1)}\left(h_2^{b+1} - h_1^{b+1}\right)$$

Virtually, there is no analytical solution, and a numerical solution has to be used. Since the integral may be undefined at the low boundary (logh not defined when h = 0), the midpoint method is used. Please see numerical textbook for details.

VOLUME BETWEEN ANY TWO POINTS

Volume calculation between any two points is identified and partitioned using the following:

- If the two points can be calculated using one equation, which means that any point in this period can be calculated using one equation, then do above.
- If the two points cross equation boundaries, then separate by breakpoints, do above for each sub-period and sum all those results from different equations.
- If the two points cross rating curves, separate by the breakpoint for rating curve and sum results together.

Calculation of streamflow inches per day
(or any time interval) over the watershed area

Don Henshaw 22 April 2010
Revised 30 May 2018

Inches of streamflow per day over a watershed is a commonly used unit for total streamflow (TOTAL_Q_AREA). Here, the general equations to calculate streamflow in inches per day (or per any time interval) are presented, as well as the areas of HJ Andrews watersheds required for these equations.

Calculation of TOTAL_Q_AREA:
Streamflow as inches per day over the watershed area

Assume:
Y = MEAN_Q (mean cubic feet per second for the day)

Then,
TOTAL_Q_ARE
A =
Y cu.ft./sec x 1/(WS area in acres) x 12 in./ft. x 1 acre/43560 sq.ft. x 86400 sec/day

Or,

TOTAL_Q_AREA = (MEAN_Q x .0002755 x 86400) / (WS area in acres)

For Andrews watersheds, use the acres values below for watershed area:

SITECODE	WS_AREA_HA	WS_AREA_ACRES
GSLOOK	6242.0	15424.0
GSWS01	95.9	237.0
GSWS02	60.3	149.0
GSWS03	101.2	250.0
GSWS06	13.0	32.0
GSWS07	15.4	38.0
GSWS08	21.4	53.0
GSWS09	8.5	21.1
GSWS10	10.2	25.3
GSWSMA	581.0	1436.0

This can be modified for any interval. Simply replace 86400 with the number of seconds in the interval, and make sure that Y is the mean cfs for that interval (MEAN_Q).

TOTAL_Q_INT = [MEAN_Q x .0002755 x (seconds in interval)]/ (WS area in acres)