# SPILLWAY CAPACITY AND DISCHARGE UNCERTAINTY – WHY DO RATING CURVES RARELY AGREE WITH FLOW MEASUREMENT RECORDS?

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Why do spillway rating curves differ from flow measurement studies or gage data? Why do rating curves often have 25% error at normal gate openings but 2% error at flood discharges? Understanding measurement uncertainty can answer these questions. This presentation compiles first-hand studies of Hells Canyon Dam, Wanapum Dam, Castlerock Dam, Petenwell Dam, and other dams. After serving as the shop manager for a university research laboratory and later transitioning to an engineering consultant, the author contends that dam owners seeking to understand rating curve discrepancies must first understand measurement uncertainty and where their rating curve originated.

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Spillway discharge coefficients have been studied, updated, and published for more than a century. So why do dam owners repeatedly find their rating curves do not match discharges published by the United States Geological Survey or other flow measurement studies?

Before studying the above quandary, let the reader first agree that owners of high hazard dams have an inherent responsibility to know 1) that their dam can pass the required flowrate and 2) the underlying accuracy of their flow discharge reports. While the first point is usually legislated, the second point is nearly as important. The National Weather Service uses reported flow release values as corrections in river forecasting models, and other dams use reported flow release values to make decisions about gate operations. Whether for water rights, flood forecasts, or run-of-river operation data, dam owners should not be reporting flow measurements with 25% or 50% errors.

The fundamental answer to this paper's question is "measurement uncertainty." Engineers have been looking at uncertainty for more than half a century, but only in the last couple decades has technology progressed such that engineers regularly apply uncertainty analysis to common calculations such as gate rating curves.[i,ii,iii,iv,v] As an explanation of uncertainty analysis, consider that all measurements (flow, velocity, head, width) have some error associated with the measurement, and this error compounds as measurements are combined into equations. If a normal probability distribution is assumed for any measurement (i.e. flowrate) as shown in Figure 1, 95% of the measurements (by number of occurrences) should fit within the hatched area and the mid-point of the hatched area is called the "Average of Repeated Results." The precision error limit is the difference between the upper end of the hatched area and the "Average of Repeated Results." If the measurement has no error, the "Bias Error Limit" would be zero. However, assuming that someone later finds that a river gauge or spillway setting consistently overestimates the flow, its "Bias Error Limit" would be positive as shown in Figure 1. The combination of "Precision Error Limit" and "Bias

Error Limit" is called "Measurement Uncertainty." An uncertainty analysis is simply studying how flow measurements are taken, what assumptions go into a calculation, how error propagates through these equations, and correctly reporting values as an "Average of Repeated Results" +/- "Measurement Uncertainty." For example, flow measurements really should be reported as 20,000 cubic feet per second plus or minus 2500 cubic feet per second. In other words, an uncertainty analysis is needed to put an expected error band around each measurement.

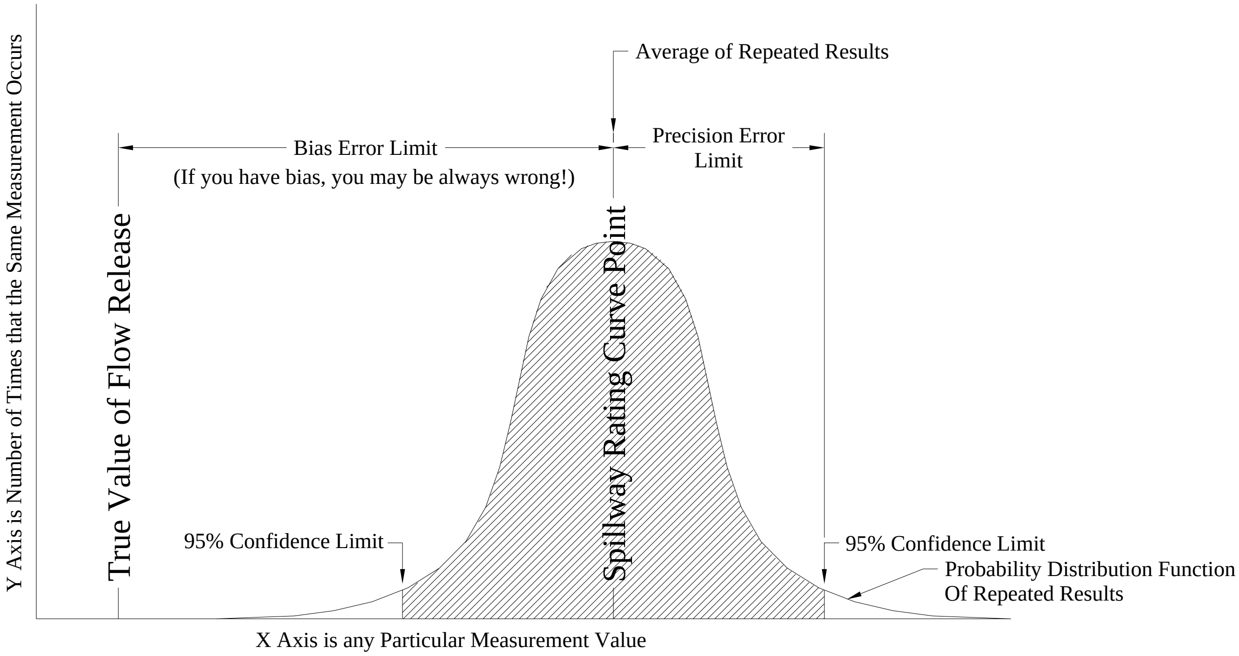

Figure 1. Normal distribution of measurement error

As a matter of practicality, Figure 2 shows a typical measurement uncertainty plot for river flow measurements. In the United States Geological Survey's class called Advanced Acoustic Doppler Current Profiler (ADCP) Applications, students learn that repeating eight to 12 passes across a river results in flow measurements with 2% to 7% uncertainty limits. Therefore, the average measurement value will be within 2% to 7% of the correct flowrate value 95 times out of 100. At the IIHR – Hydroscience & Engineering, researchers reported spillway flows from large[vi] scale models as 0.6% for full gate open tests to 11% for the smallest (0.5 inch usually) gate openings. Note that even a guess has some uncertainty limit, based on the user's familiarity and skill. By combining uncertainty information for all sources of uncertainty at a dam, the dam owner can now expect a (quantifiable) difference between river gauge measurements and reported dam discharges.

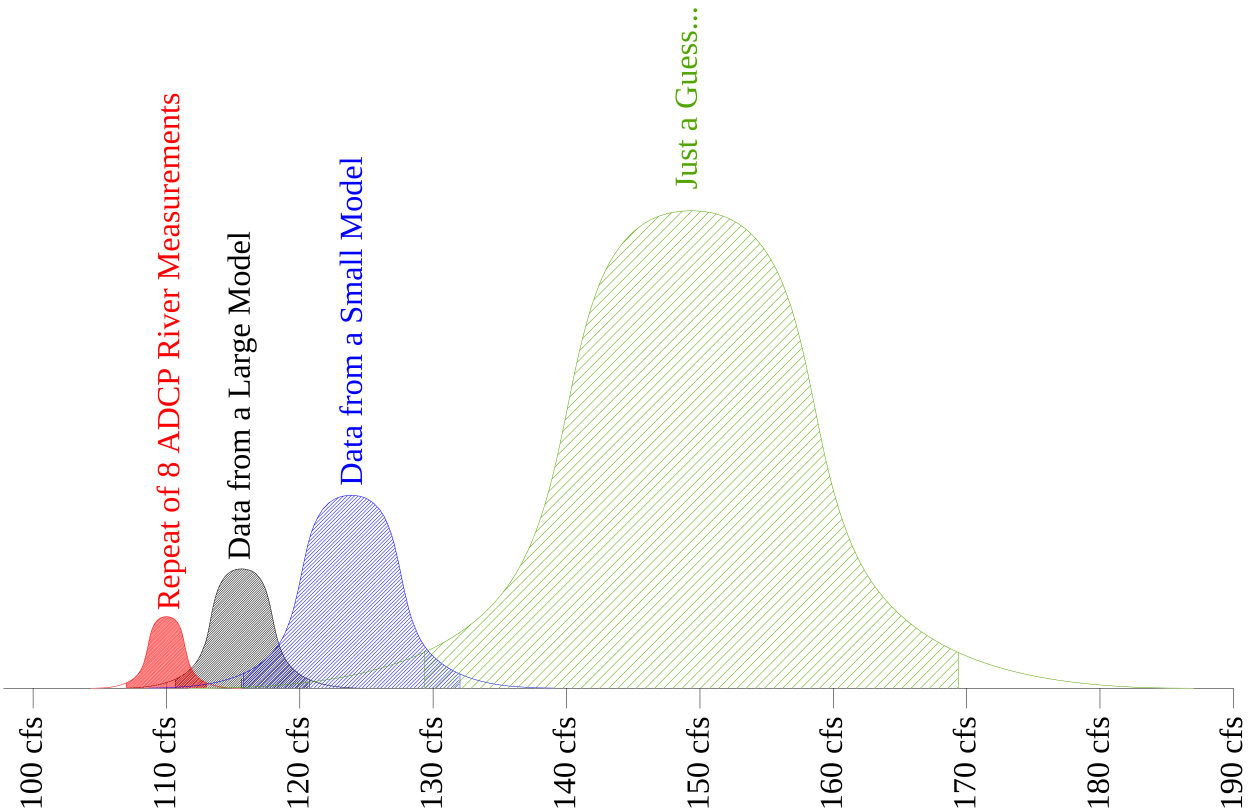

Figure 2. Example of measurement uncertainty for river flowrates

Once a dam owner realizes that the accuracy of the river flowrate data is just as important as the reported flow value, discrepancies between USGS data and dam discharges should be answered by the following thought progression:

1. Is the dam's reported flow value based on a theoretical equation, a model study, an engineering guess, or a rating curve of dubious origin?
2. Is the river flowrate data based on calibrated, repeated, and verified measurements?
3. Is the difference between the above two flows within the reasonable uncertainty limits?

Until the answers to the above questions are answered, the dam owner can never be certain which flow measurement or reported value is (most) correct.

Consider these statistics: Based on my 12 years of testing model spillways in the laboratory, published spillway rating curves for low and normal flow gate openings often have 25% to 35% error even though the rating curve error is less than 2% at flood discharges. This high measurement uncertainty (error) at normal flow gate openings is attributable to three primary causes.

First, measurement uncertainty often arises because rating curves for standard spillway shapes and most large dams were developed from model studies where small gate openings exacerbated model similitude issues and flow measurement uncertainty propagation. In other words, model scales and flowmeters are usually selected for the highest river discharge which is often the full gate open, probable maximum flood, and deepest water depth condition. In reality, normal flow conditions in these models may not satisfy minimum similitude values, especially the Weber (surface tension) and Reynolds (turbulence) numbers. Therefore, while these scale models accurately predict flood discharge coefficients, they often grossly err for low flow conditions.

Second, measurement uncertainty results when as-built gate geometry does not exactly match what was modeled. For example, Wanapum Dam's final design shifted the gate's trunnion position without a proportional change in gate sill elevation. The result was a significant change in the gate lip to crest angle which produced high discharge errors at low gate openings but insignificant errors during the flood discharge conditions. Castle Rock and Petenwell Dams are nearly identical, except that the corbelled ogee was never built at Castle Rock as it was at Petenwell and the discharge performance is significantly different now. Similarly many dams' final designs were not exactly proportioned to the standard USACoE or USBR profiles, and yet their rating curves are based on the standard profile design values.

The third source of measurement uncertainty arises simply because all measurements have uncertainty and by combining different measurements the uncertainty grows (propagates). Even if a measurement is proven to have no bias (regular and consistent shift from the true value), this measurement always has a precision (repeatability) uncertainty. For instance, USGS flow measurements below dams are usually completed with ADCP equipment which has a great success rate on open rivers with generally uniform flow conditions. However, even if no power lines were nearby to affect the ADCP compass and no bubbly flows interfered, the ADCP measurements *still* have a precision uncertainty which is the inaccuracy due to flow circulations, turbulence, and a host of other variables with randomly-distributed errors. Understanding this third source of measurement uncertainty means that a flow measurement with 5% uncertainty and a gate rating curve with 10% uncertainty might both be considered "accurate" and "correct" even though the discharges are 15% different.

The three sources of uncertainty were repeatedly observed from 1998 to 2005 when the author helped the University of Iowa's IIHR-Hydroscience & Engineering study spillway gates for large dams along the Snake and Columbia Rivers. Specifically, data from scale models of Idaho Power Company's Hells Canyon Dam[vii,viii] and Grant County Public Utility District's Wanapum Dam[ix] were compiled and compared against design standards[x,xi,xii], earlier model tests[xiii,xiv], and various theoretical rating curves[xv,xvi]. After this author became a consultant with Ayres Associates in 2010, this research continued as spillway rating curves for Castle Rock Dam[xvii], Petenwell Dam[xviii], and several other dams were also evaluated and compared to design standards and earlier model tests[xix,xx]. In comparing all of this data, the following generalizations were concluded.

1. Scale models smaller than 1/50 can have more than 15% error just due to viscous scale effects.
2. Scale models that do not account for three-dimensional (3D) flow variability can misrepresent effective head by several feet. (It is surprising how many complex spillways are rated with only a single bay model with insufficient upstream bathymetry and approach flow distances.)
3. Full gate open discharge coefficients are usually within 2% of the standard USACoE design figures at the dam's design flow capacity.
4. Partial gate open discharge coefficients are very sensitive to small changes in gate lip to crest angle, trunnion position, gate radius, and approach flow conditions.

Figure 3 illustrates the complex relationship between partial gate opening (beta angle is a non-dimensional representation of gate opening distance) and discharge coefficient. Even though Figure 3 shows a wide range of hydraulic performance, all of these dams have similar spillway ogees, tainter gates, and piers as shown in Table 1.

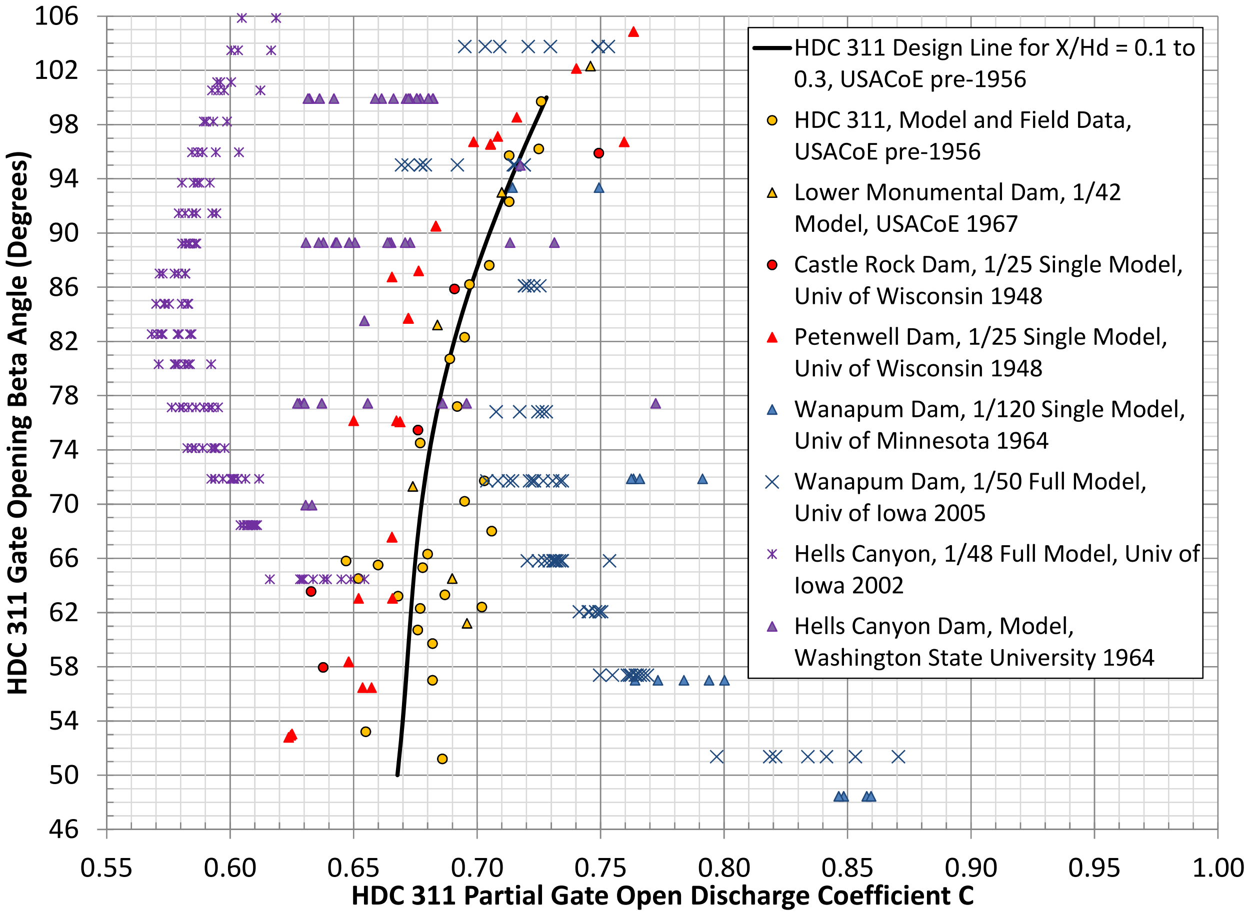

Figure 3. Partial gate open discharge performance for five dams with similar ogee, pier, and tainter gate geometry

|  | Wanapum Dam | Hells Canyon Dam | Castle Rock Dam | Petenwell Dam | Lower Monumental Dam |
|---|---|---|---|---|---|
| Owner | Grant County PUD | Idaho Power Company | Wisconsin River Power Company |  | USACoE |
| Location | Columbia River | Snake River | Wisconsin River | Wisconsin River | Snake River |
| Total Spillway Length | 765 ft | 159 ft | 560 ft | 630 ft | 498 ft |
| Number of Tainter Gates | 12 ft | 3 ft | 16 ft | 18 ft | 8 ft |
| Tainter Gate Width | 50 ft | 42 ft | 30 ft | 30 ft | 50 ft |
| Tainter Gate Height | 65 ft | 50.6 ft | 19.7 ft | 19.7 ft | 60.6 ft |
| Tainter Gate Radius | 64.5 ft | 51.5 ft | 18 ft | 18 ft | 60 ft |
| Spillway Structural Height | 119 ft | 296 ft | 63.3 ft | 78.5 ft | 165 ft |
| Spillway Crest Equation | Y=0.020X^1.80 | Y=0.023X^1.85 | Y=0.029X^1.99 | Y=0.029X^1.99 | Y=0.025X^1.85 |
| Approach Flow Shape | Radiused Vertical | Radiused 1H:25V | Radiused Vertical | Radiused Corbel | Radiused Vertical |
| Pier Shape | Type 3 | Type 3 | Type 3 | Type 3 | Type 3 Elliptical |

Table 1. Geometry comparison for dams studied in Figure 3

Looking in Figure 3, data for the same dam often differs because of viscous scale effects (small scale size), a lack of 3D approach flow conditions (simplified model), and a slight rotation of the tainter gates during construction (design change). All of the standard USACoE ogee dams (yellow points and black line) are similar because they have very exact design specifications, but even those points have a discharge coefficient uncertainty no less than +/- 0.04 (6%).

So even if a rating curve is unfounded or has significant differences when compared against neighboring river gauge reports, an engineering uncertainty analysis can determine where errors are most likely, develop methods to achieve less total uncertainty, and create better rating curves for dam owners.

In conclusion, dam owners should be prepared to answer where their spillway discharge rating curves originated and the accuracy (or uncertainty) of those curves. When discrepancies arise between USGS gauge flows, spillway discharge reports, and even multiple model studies, the solution is to re-evaluate the original data and understand how the USGS gauge data with perhaps 5% uncertainty differs from the dam’s hydraulic model study data with perhaps 10% uncertainty. In the end, as long as the shaded area of Figure 1 overlaps for both data points – they could be statistically indistinguishable. However, based on the author’s personal experience, often rating curves have large errors (25% or more) simply because no one has properly evaluated where the data originated and if it correlates with the as-built dam conditions.

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## Author

Between post-graduate studies and a shop manager position at IIHR, Pete Haug spent more than 10 years researching spillway performance, river flow measurements, and gate hydraulics. After transitioning from IIHR in 2010, Mr. Haug continues these hydraulic studies as a project manager for Ayres Associates in Eau Claire, Wisconsin.

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