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# Performance Limits of Width-Contracted Flumes

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## ABSTRACT

Long-throated flumes and broad-crested weirs are economical and flexible devices for measurement of open-channel flows. These structures produce critical depth flow in a throat section created by a raised sill, contracted width, or a combination of floor and sidewall contractions. Flumes that are solely width-contracted are especially suitable for sites where bed load must be transported through the measurement structure. The hydraulic theory used to predict the contraction required for critical flow and determine the head-discharge rating of a structure assumes that width contractions and floor contractions are equally effective. In most cases this is true, but in width-contracted flumes whose throat sections are very wide compared to their length, the flow disturbance created by the side wall contraction may not propagate sufficiently across the channel before the flow exits the throat. The effect of the side walls is not felt at the centerline of the throat section and critical depth may not occur uniformly in the throat section. To examine this phenomenon, a series of flumes with similar geometry but with different throat length to width ratios was tested to determine operational limits of width-contracted flumes. The modular limits of the widest flumes were found to be lower than the values predicted by theory. Guidelines for design of width-contracted flumes are provided.

## INTRODUCTION

The term *long-throated flume* describes a large family of critical-flow flumes and broad-crested weirs used to measure open-channel flows. Many specific configurations are possible, depending on the type of approach channel, the shape of the throat section, the location of the gaging station, and the use or lack of a diverging transition section. Computer software for rating and designing flumes (WinFlume) is available for free download on the Internet at www.usbr.gov/wrrl/winflume/ (Wahl et al. 2000), and detailed design, construction, selection, and operational guidance is provided in Clemmens et al. (2001).

Long-throated flumes have particular advantages compared to more traditional devices, such as Parshall flumes. These older devices are laboratory-calibrated, because the flow through their control sections is curvilinear. In contrast, the streamlines are essentially parallel in the throat sections of long-throated flumes, making it possible to rate them analytically. Primary advantages of long-throated flumes include:

- Rating table uncertainty of ±2% or better in the computed discharge.
- Choice of throat shapes allows a wide range of discharges to be measured with good precision.
- Minimal head loss needed to maintain critical flow conditions in the throat of the flume.
- Ability to make field modifications and perform computer calibrations using as-built dimensions.
- Economical to construct, and adaptable to a variety of existing canal configurations.

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Long-throated flumes and broad-crested weirs can create a flow contraction either by a raised sill (a vertical contraction), a narrowed throat section (a width contraction), or a combination of both features. One issue that has arisen in recent years is the rating of structures that are primarily width-contracted. The hydraulic theory used to rate the structures and determine the required contraction to produce critical flow assumes that vertical contractions and width contractions perform identically. However, in the case of flumes having very wide, short control sections, this is not true. Such flumes do not produce uniform, critical-depth flow conditions across the full width of the throat, because the width contraction does not influence the flow at the centerline of the flume. The flow disturbance created at the beginning of the side wall contraction cannot propagate to the center of the flume before the flow is carried off the downstream end of the throat section. This has the potential to change the rating of the structure or its modular limit (the maximum submergence ratio for which critical flow is maintained).

To study this phenomenon and develop suitable design guidance for avoiding the problem in new flume designs, a series of flumes were built and tested in the hydraulics laboratory of the Bureau of Reclamation. The flumes had similar geometric properties, but varying throat width-to-length ratios. These flumes were tested over a range of flow rates and tailwater conditions and their ratings and modular limits were compared to those predicted by analytical methods using the WinFlume computer program.

## EXPERIMENTAL SETUP

Testing was carried out in a 1.22-m (4-ft) wide glass-walled laboratory channel. Figure 1 shows the layout of the test facility. Flow passed through two sets of baffles, then traveled about 5.5 m (18 ft) to the test section. The floor of the test section was elevated about 0.3 m (1 ft) above the concrete floor of the laboratory channel. The test section was approximately 4.6 m (15 ft) long and included the approach channel for each tested flume, a static tube used to sense the water level at the gaging station location, and the converging transition section and throat section of each tested flume. The tailwater channel downstream from the test section was about 9.1 m (30 ft) long. Tailwater levels were set by stoplogs installed at the downstream end of the facility.

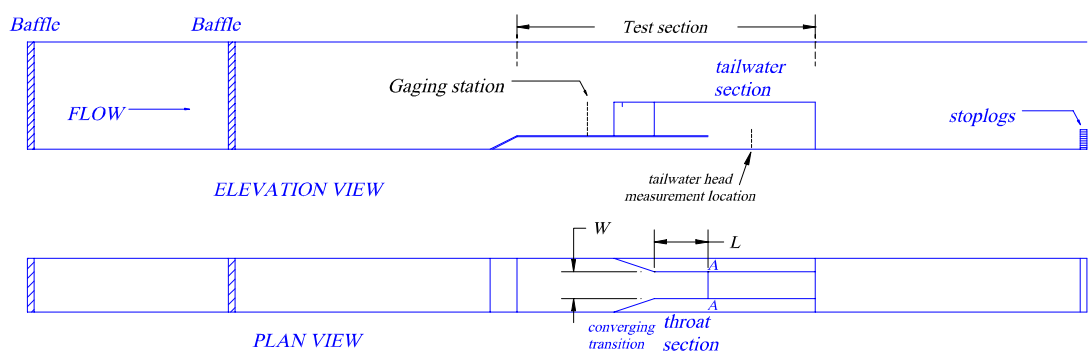
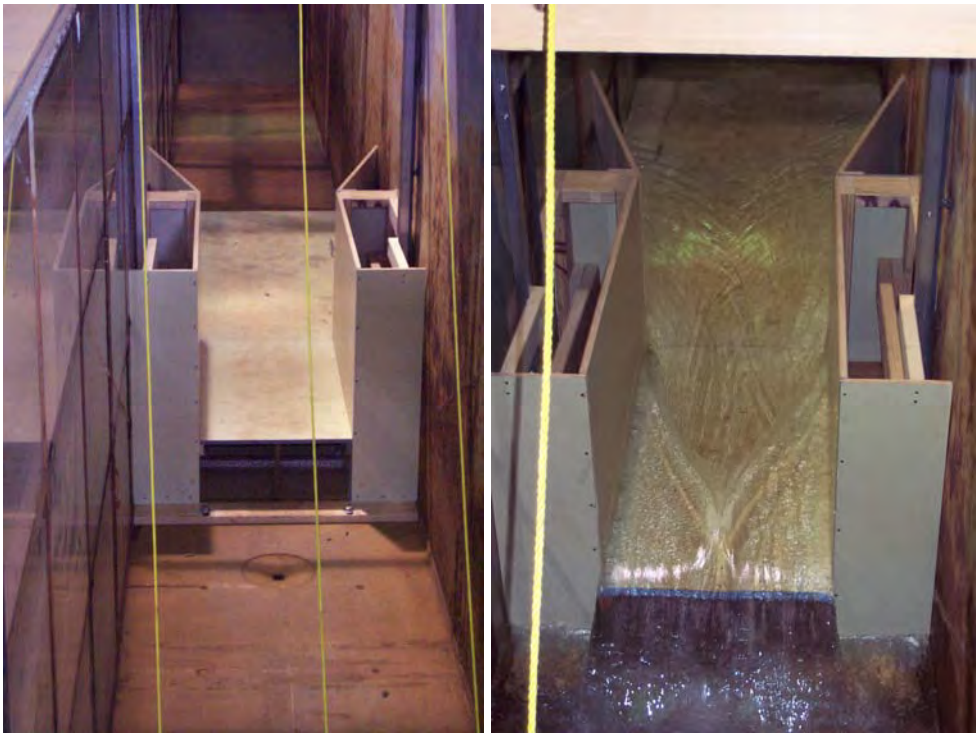



**Figure 1. — Laboratory test channel and typical long-throated flume in test section.**

Long-throated flumes were constructed in the test section (Fig. 2) and operated at a range of flow rates and tailwater conditions. For each test, the upstream sill-referenced head on the flume was measured using a hook gage mounted in a stilling well (estimated measurement uncertainty ±0.001 ft), and the discharge through the flume was determined using the laboratory's fixed

venturi flow meters, which have a measurement uncertainty of less than ±0.5%. The tailwater levels relative to the sill elevation were also recorded. For each test condition, the observed rating (head vs. discharge relationship) was compared to the rating determined analytically by the WinFlume software.



(a) (b)

**Figure 2. — Flume A (a) prior to testing and (b) operating at 0.141 $m^3/s$ (5 $ft^3/s$). Both photos were taken looking upstream.**

## *Test Flumes*

The tested flumes shared several characteristics. All utilized rectangular-shaped approach, throat, and tailwater sections, and the contraction from the approach channel section (i.e., the gaging station location in Fig. 1) to the throat section was created entirely by a reduction of the channel width. The throat width, *w*, was held constant at 0.648 m (25.5 inches) for all flumes except one; on the last flume tested (E) the throat width was reduced to 0.495 m (19.5 inches). The principal difference between the different tested flumes was the length of the throat section, *L*. This length was varied from about 1.22 m (4 ft) down to 0.32 m (12.75 inches). This was accomplished by reducing the length of the floor of the throat section, which changes the position of line A-A shown in Figure 1. The majority of the tested flumes used a tailwater channel whose width matched that of the throat section, although one flume (A) was tested with a 1.22-m (4-ft) wide tailwater channel, approximately twice the width of the throat section (Fig. 2). Table 1 summarizes the dimensions of the tested flumes. The table indicates the approximate Froude number in the approach channel (at the gaging station location). For each flume, the Froude number changes only slightly as the flow rate is varied. Flumes were generally tested at flow conditions in the recommended range of $0.07 \leq H_1/L \leq 0.7$, where $H_1$ is the upstream sill-referenced energy head.

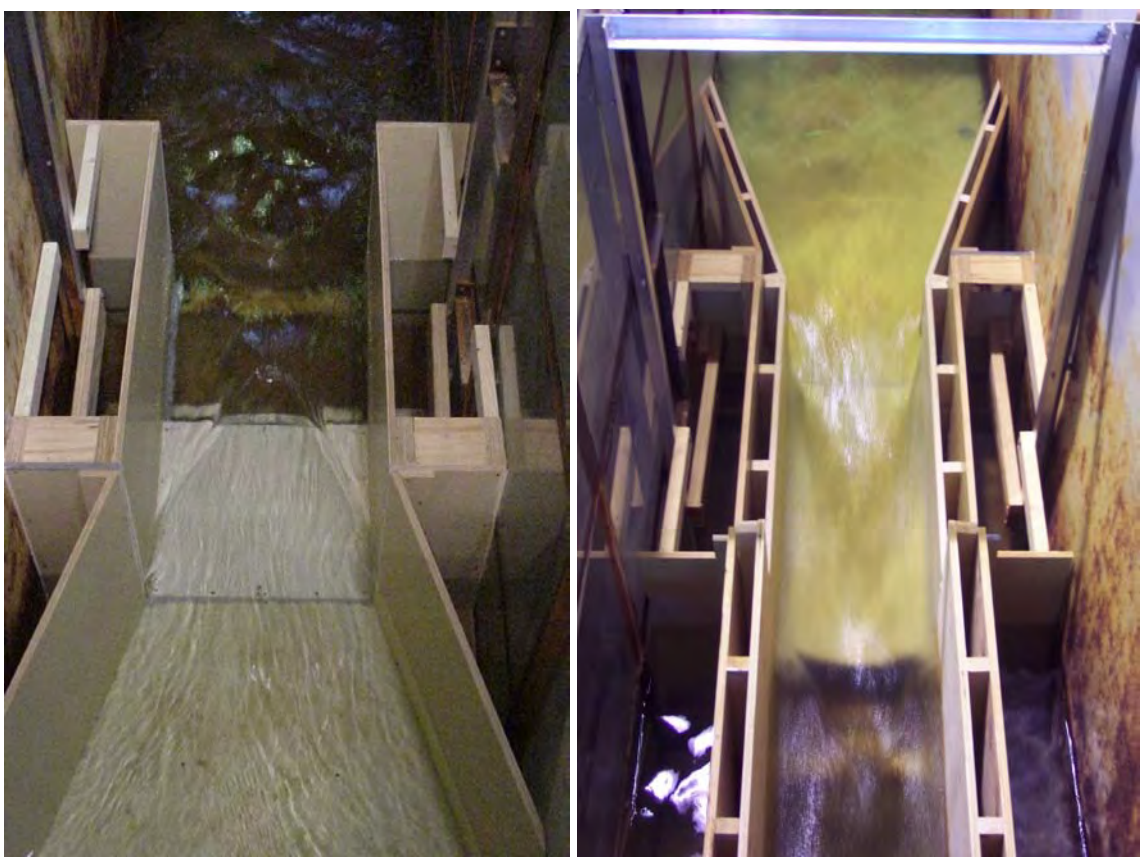
**Table 1. — Tested flumes.**

| Flume | Range of discharges tested ($m^3/s$) | Approach channel Froude number | Throat width, *w* (m) | Throat length, *L* (m) | *L/w* | Tailwater channel width (m) | Modular limit, range |
|---|---|---|---|---|---|---|---|
| A | 0.028 – 0.697 | 0.30 | 0.648 | 1.238 | 1.91 | 1.219 | 0.65 – 0.79 |
| B | 0.028 – 0.326 | 0.30 | 0.648 | 0.648 | 1.00 | 1.219* | 0.70 – 0.86 |
| C | 0.028 – 0.113 | 0.30 | 0.648 | 0.324 | 0.50 | 0.648 | 0.70 – 0.80 |
| D | 0.266 | 0.30 | 0.648 | 1.238 | 1.91 | 0.648 | 0.85 |
| E | 0.268 | 0.22 | 0.486 | 1.238 | 2.55 | 0.648 | 0.86 |

* Flume B discharges initially into a channel of width 0.648 m, then abruptly expands to 1.219 m. The tailwater head measurement takes place in the section that is 1.219 m wide.

## TEST RESULTS

For each test flow, the measured upstream head was used to compute the flow through the structure using the analytically determined flume rating equation, and this result was compared to the actual discharge as determined by the laboratory venturi meters. Figure 3 shows Flumes B and E in operation.



(a) (b)

**Figure 3. — (a) View looking downstream at flume B, operating at a flow rate of 0.113 $m^3/s$ (4 $ft^3/s$) at a tailwater level approaching the modular limit, and (b) looking upstream at Flume E operating at 0.268 $m^3/s$ (9.46 $ft^3/s$) with a low tailwater setting.**

Figure 4 shows the flow measurement error (flume rating compared to actual discharge) as a function of the submergence ratio, $H_2/H_1$, where $H_2$ is the energy head in the tailwater channel. At low submergence ratios one expects the measurement error to be within the predicted measurement uncertainty of the flume, accounting for both rating table uncertainty and head-measurement uncertainty. This measurement uncertainty is estimated by WinFlume as part of the rating process, and for all flumes tested here was approximately ±2%. Figure 4 shows that for submergences less than 60% the observed measurement error is generally in the range of ±2%. It should be noted that all submergence values less than zero are plotted at a submergence of zero because negative submergence is meaningless and because tailwater levels below the sill of the flume could not be registered in the stilling well used for the testing. For submergences greater than about 60%, measurement errors begin to exceed the ±2% range for the flumes with $L/w$ = 0.5 and $L/w$ = 1, and increase dramatically when the submergence exceeds about 80%. It should be noted in Table 1 that the theoretical modular limits of all the tested flumes are greater than 60% for all tested flow rates, and are 80% or more for the highest flow rates. The flumes with $L/w$ = 1.9 and $L/w$ = 2.55 match their theoretical ratings up to submergence values exceeding 80%, except for flume A, which has a length-to-width ratio of $L/w$ = 1.9, but with an abrupt expansion into a 1.22-m (4-ft) wide tailwater channel. This causes the theoretical modular limit of this flume to be lower (see Table 1), and thus the higher measurement error at a submergence value of about 70% is expected.

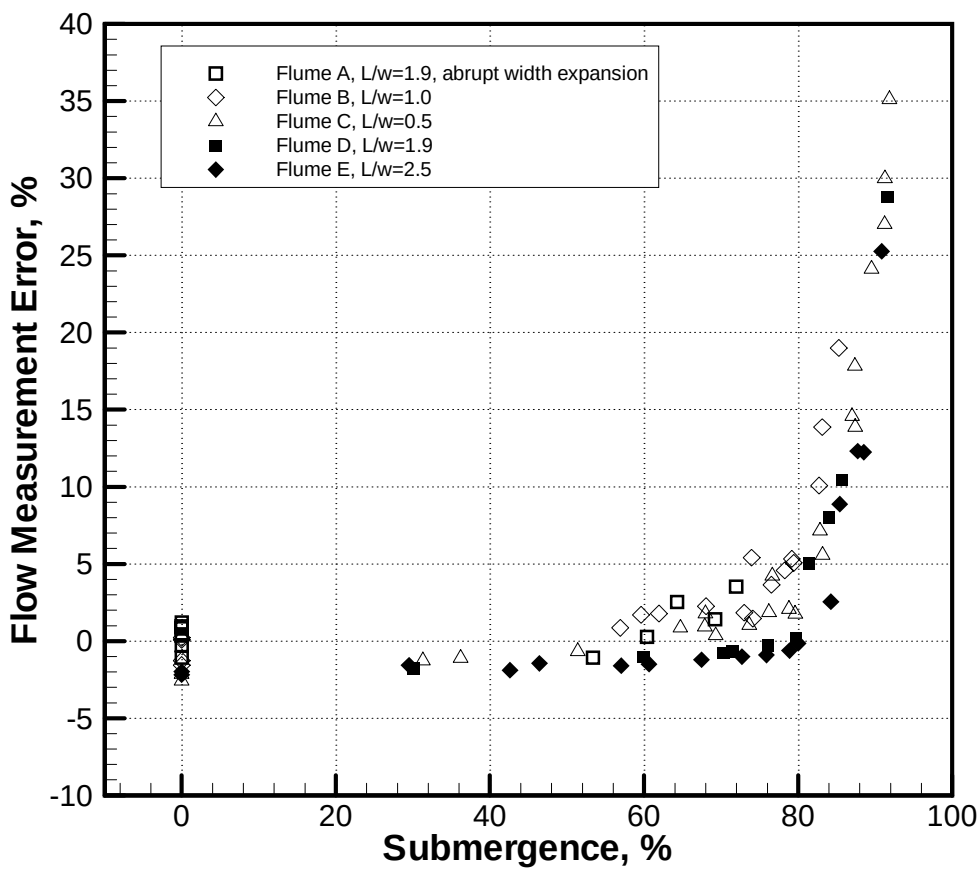



**Figure 4. — Flow measurement errors as a function of submergence.**

The 60% submergence level is of significance because this is the theoretical modular limit for flumes having a rectangular control section discharging via an abrupt expansion into an infinite pool (Clemmens et al. 2001, pg. 257). Any rectangular-throated flume operating at a submergence level below 60% should be operating in a free flow condition. Thus, Figure 4 indicates that for free-flowing conditions, all of the tested flumes match the theoretical ratings, but additional submergence affects the ratings sooner than expected (at lower submergence ratios than the theoretical modular limit).

Figure 5 shows the flow measurement error as a function of the excess submergence (the actual submergence minus the theoretical modular limit). Viewing the data in this manner helps account for the fact the modular limit of each flume is different and also varies with flow rate. When excess submergence is lower than -15% (i.e., more negative), data generally plot within the ±2% uncertainty band, but when excess submergence is above -15% (i.e., submergence is within 15% of the modular limit), the flumes with $L/w$ = 1 and $L/w$ = 0.5 exhibit errors outside of the expected ±2% uncertainty. The flumes with $L/w$ = 1.9 and $L/w$ = 2.55 reasonably match theoretical ratings up to excess submergence values near zero, meaning that the actual modular limit of these flumes is equal to the theoretically determined value. Thus, on the basis of these tests, it appears that width-contracted flumes become more sensitive to submergence effects when the $L/w$ ratio is something less than 1.9. When $L/w$ is 1.9 or greater, width-contracted flumes perform as expected.

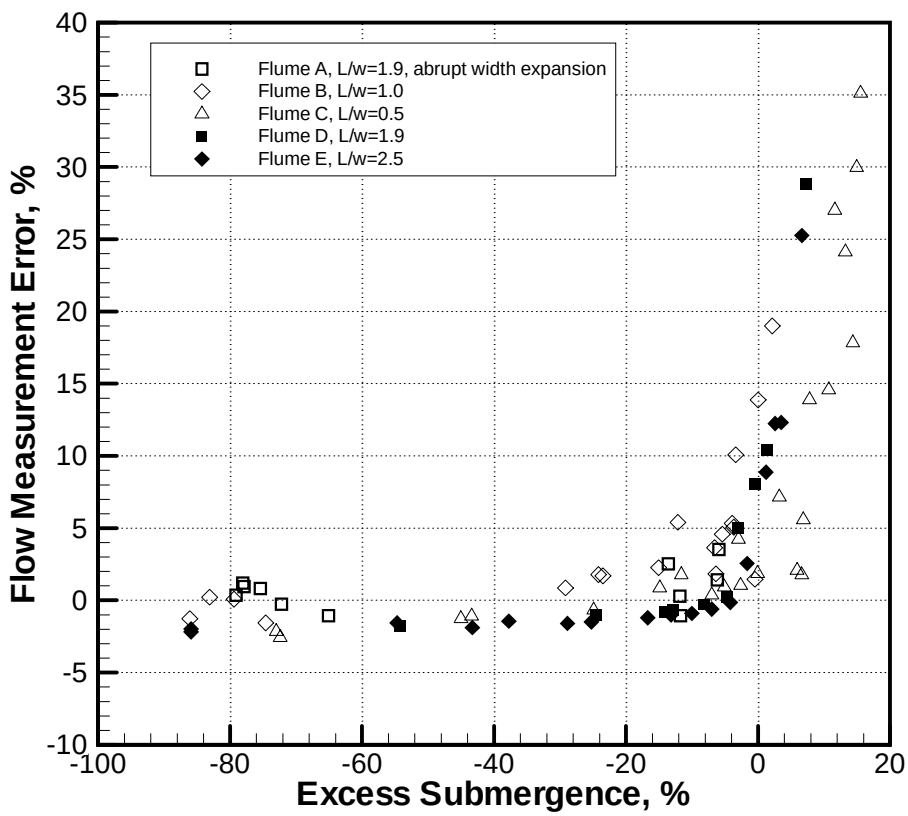



**Figure 5. — Flow measurement errors as a function of the excess submergence (actual submergence minus the theoretical modular limit).**

## CONCLUSIONS AND RECOMMENDATIONS

A set of rectangular-throated flumes that are solely width-contracted have been found to match theoretically determined ratings up to a submergence ratio of about 60%, which is the expected modular limit of a rectangular-throated flume discharging into an infinite reservoir through an abrupt expansion. When tailwater levels were sufficiently low, even very wide flumes with short throat sections experienced a uniform critical-depth flow condition in the control section and properly matched their theoretical ratings up to the 60% submergence level. For submergences greater than 60%, width-contracted flumes with a throat length-to-width ratio of less than 1.9 are affected by submergence and will not match theoretical ratings; the modular limit of these flumes is less than that predicted by theory. This is believed to be due to submergence affecting the flow near the longitudinal centerline of the flume. Along the centerline, critical-flow conditions cannot be established due to the high tailwater and the inability of the flow in the throat to transmit the disturbance from the sidewall to the centerline of the flume within the available throat length. The exact length-to-width ratio at which the modular limit of width-contracted flumes drops below the theoretical value was not determined, but is in the range of $L/w = 1$ to $L/w = 1.9$.

For designers of flumes that are solely width-contracted, two options are available. When the throat length-to-width ratio is kept greater than 1.9 (or 2 for simplicity), width-contracted flumes should perform exactly as expected, with a head-discharge rating that is analytically predictable up to the predicted modular limit. If the $L/w$ ratio is less than 2, then the designer should ensure that the submergence on the flume, $H_2/H_1$, does not exceed 60%. Higher submergence limits may be acceptable for width-contracted flumes with trapezoidal, parabolic, or triangular control sections, since these shapes are inherently more tolerant of submergence, but such flumes have not been tested at this time, and thus the 60% submergence limit is suggested for all width-contracted flumes when $L/w$ is less than 2.

## REFERENCES

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