WINFLUME — WINDOWS-BASED SOFTWARE FOR THE DESIGN OF LONG-THROATED MEASURING FLUMES

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ABSTRACT

Long-throated flumes and broad-crested weirs provide a practical, low-cost, flexible means of measuring open-channel flows in new and existing irrigation systems, with distinct advantages over other flume and weir devices. A primary advantage is the fact that these structures can be custom-designed and calibrated with a computer program based on well-established hydraulic theory. This allows the design of structures that meet unique operational and site requirements, and eliminates the need for laboratory calibration. To facilitate future use of these devices, the Bureau of Reclamation and the Agricultural Research Service have recently developed the Windows-based, WinFlume computer program described in this paper.
KEYWORDS. Flumes, Weirs, Water measurement, Flow measurement, Software programs

INTRODUCTION

The term *long-throated flume* describes a broad family of critical-flow flumes and broad-crested weirs used to measure open-channel flows. A variety of specific configurations are possible (Fig. 1), 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. Bos et al. (1984) described the theory for determining discharge through these flumes. Several incremental improvements in computer programs used to rate (Clemmens et al., 1987) and design (Clemmens et al., 1993) long-throated flumes have preceded the development of the WinFlume computer program described in this paper.

In recent years long-throated flumes have become the measurement device of choice for most applications (Reclamation, 1997), superseding Parshall flumes and other traditional devices. These older devices were laboratory-calibrated, because the flow through their control sections is curvilinear. In contrast, streamlines are essentially parallel in the control sections of long-throated flumes, making them amenable to analysis using straightforward hydraulic theory. Significant advantages of long-throated flumes include:

- Rating table uncertainty of ±2% or better in the computed discharge.

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- 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 construction and adaptability to varying site conditions.

The calculations needed to calibrate, size, and set flumes are iterative, and as a result, several generations of computer codes have been developed for these purposes in recent years, initially by the Agricultural Research Service (ARS) at the U. S. Water Conservation Laboratory in Phoenix, Arizona, USA. Early programs operated in a batch mode and were written in FORTRAN. In the early 1990's ARS and the International Institute for Land Reclamation and Improvement (ILRI) contracted for the development of an interactive computer program for long-throated flume design. That program (Clemmens et al., 1993), known as FLUME 3.0, was written in the Clipper language and operated in an MS-DOS computing environment. Recent advances in computer technology
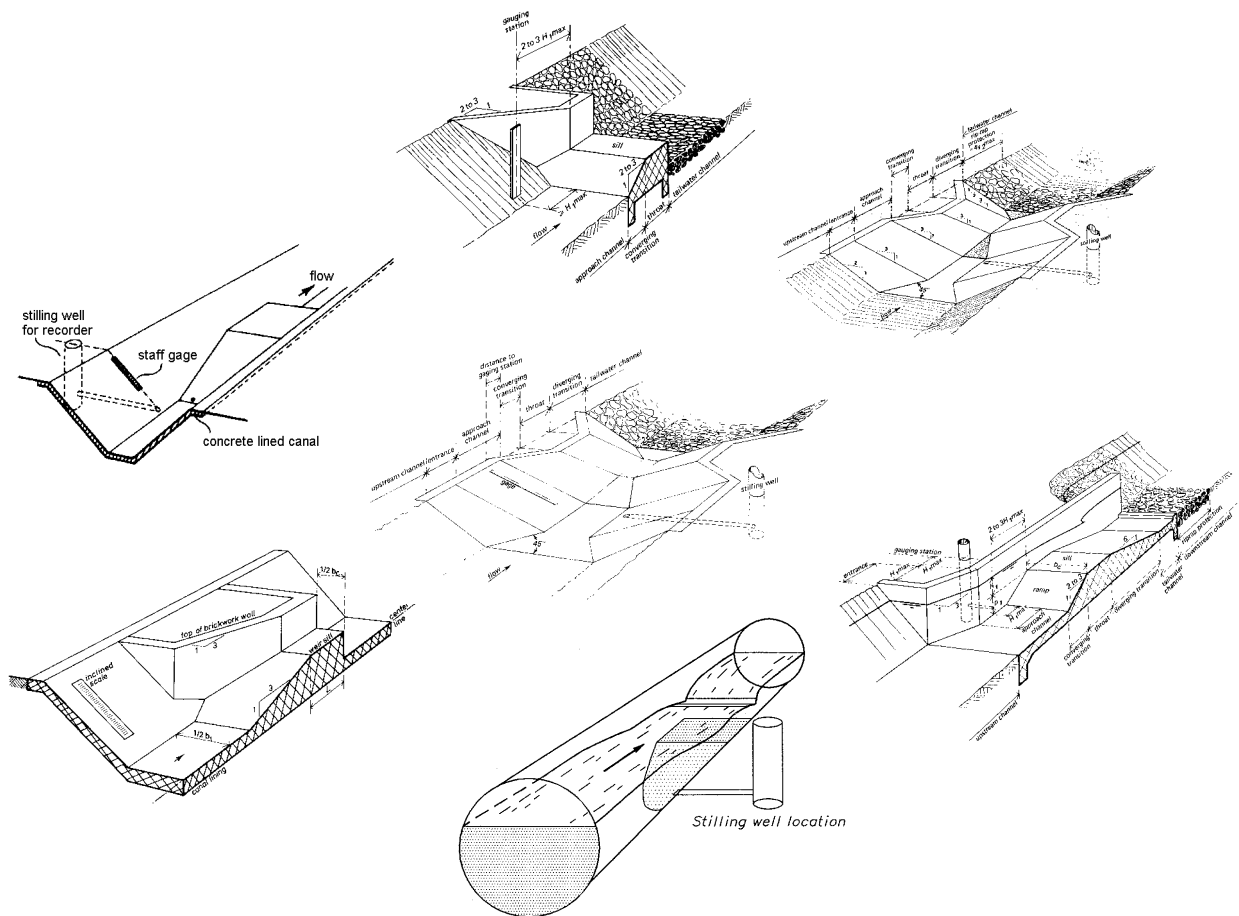

Figure 1. — Many Flume and Weir Configurations Meet the
Requirements for Analysis as Long-Throated Flumes.

have made that program obsolete.

In 1997 the Bureau of Reclamation (Reclamation) and ARS began cooperative work on an updated version of the flume design software. The new program, WinFlume, is targeted at the Windows 95/NT environments, and also operates under Windows 3.x. WinFlume makes use of the same hydraulic theory used in its predecessors, but has an improved user interface, a new design module, and other new features. WinFlume was programmed in-house by Reclamation to facilitate future maintenance and improvement of the software.

THE WINFLUME COMPUTER PROGRAM

WinFlume was developed as a native Windows 95 and Windows NT application, using the Visual Basic programming language. The application is compiled into a 32-bit executable for Windows 95/NT systems and a 16-bit executable for Windows 3.x systems. Graphical output from the program (e.g., head-discharge curves, plots of rating equations, comparisons to measured flows) is provided using an integrated third-party graphics library that is distributed royalty-free with the program.

Internally, the program is object-oriented, with the definition of a flume and its associated channel and hydraulic properties contained in a single structured data type. This simplifies storage and retrieval of flume designs and manipulation of multiple "virtual" flumes in the design module. WinFlume works internally in SI units, but allows the user to choose from a wide variety of other units for data input and output. The units preferences of each flume design are stored as a part of the flume file.

Operation of the program is centered around an editable graphic display of flume dimensions (Fig. 2), auxiliary screens used to specify design requirements and other data, and several screens devoted to analysis, review, and output of flume designs. Bottom-profile dimensions are edited from the main screen, while cross-sections are edited in another screen that shows additional detail. Seven different cross-section shapes are available for the approach and tailwater sections of a flume, and 14 control-section shapes are available, including circular, parabolic, trapezoidal, and complex shapes.

In addition to the flume and canal geometry, the user must define hydraulic properties of the structure and the site, and design requirements to be used for later evaluation and review of flume designs. Specific information needs include:

- The hydraulic roughness of the material used for construction of the flume.
- Range of flows to be measured and the associated tailwater levels at the site.
- Allowable flow measurement uncertainty at minimum and maximum discharge.
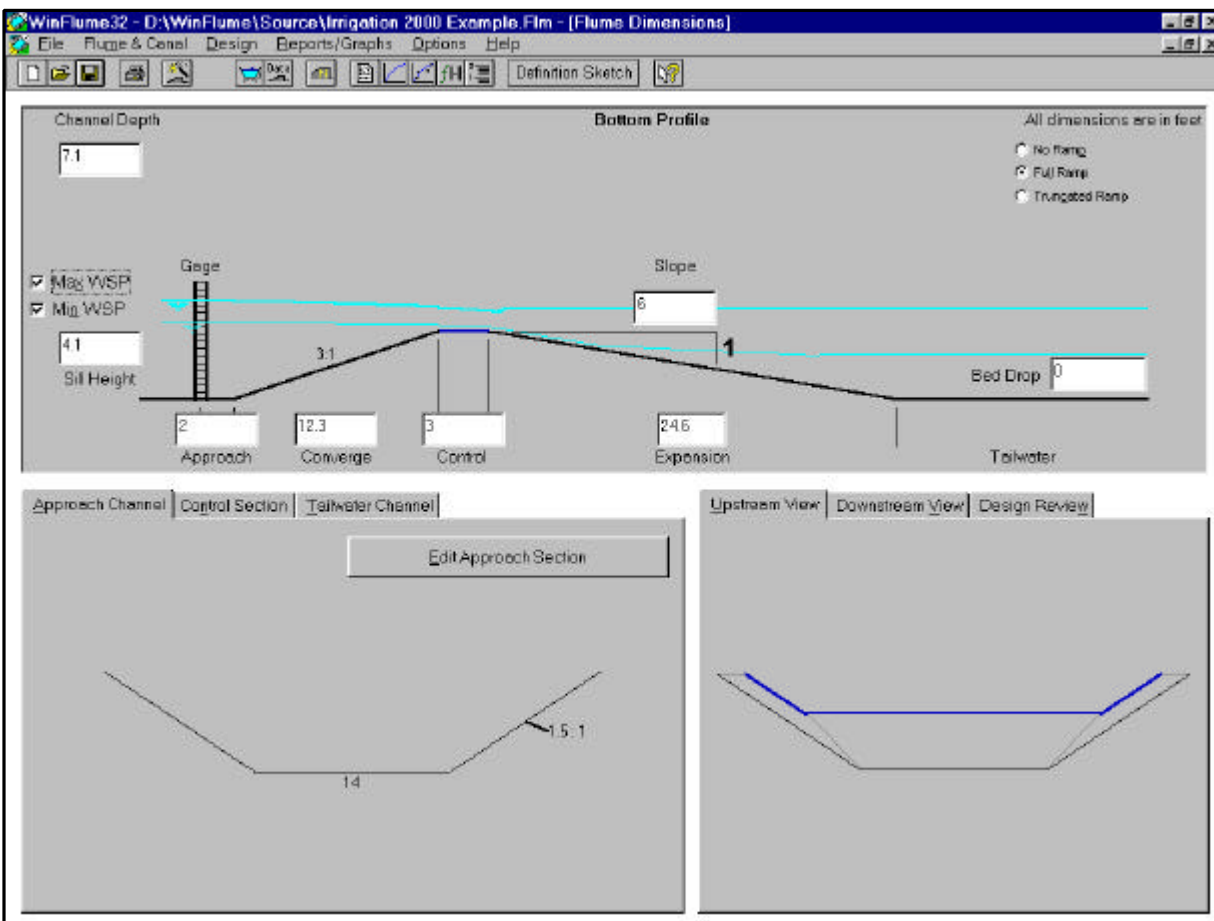- Required freeboard in the approach channel at maximum flow.

Figure 2. — WinFlume's Main Screen Shows the Flume and Canal Geometry.

Basic capabilities of the WinFlume program include: the development of rating tables, rating equations, and related output for existing structures; review of new designs against basic design criteria and user-specified design requirements; and automated evaluation of a range of flume designs to identify those designs that meet specific head loss objectives.

The WinFlume program supports all features of the previous FLUME 3.0 program, and contains a number of new and improved features. The most dramatic improvements are in the user interface, which takes full advantage of the Windows environment and includes such features as a top menu bar, toolbars, tabbed dialog boxes to organize program features, spreadsheet grids to display rating table data, and standard dialog boxes for loading and saving files. All output can be directed to a file, the system clipboard, or any Windows-compatible printer. The integrated help system provides both flume-design guidance and program help. A printable user's manual in Adobe Acrobat format is also provided with the program.

Wall Gages: A major new feature of WinFlume is the ability to print full-size flume wall gages (Fig. 3). Gages may be graduated in either head or discharge units, to be installed vertically in the upstream pool or on the sloped bank of the approach channel. WinFlume provides an on-screen preview of the wall gage and can then print it at full scale to any Windows printer. Controls are provided for adjusting label sizes, labeling intervals, and number display format. With a roll-feed

plotter, wall gages can be printed on a continuous sheet of paper. With smaller page printers, WinFlume will split the gage into several sections and print each on a separate sheet of paper with the match marks needed to reconstruct the continuous gage. These full-size paper gages can then be provided to a fabricator for construction of a durable field-quality gage.

Flume Wizard: To assist new users of the program or those wishing to take a consistent step-by-
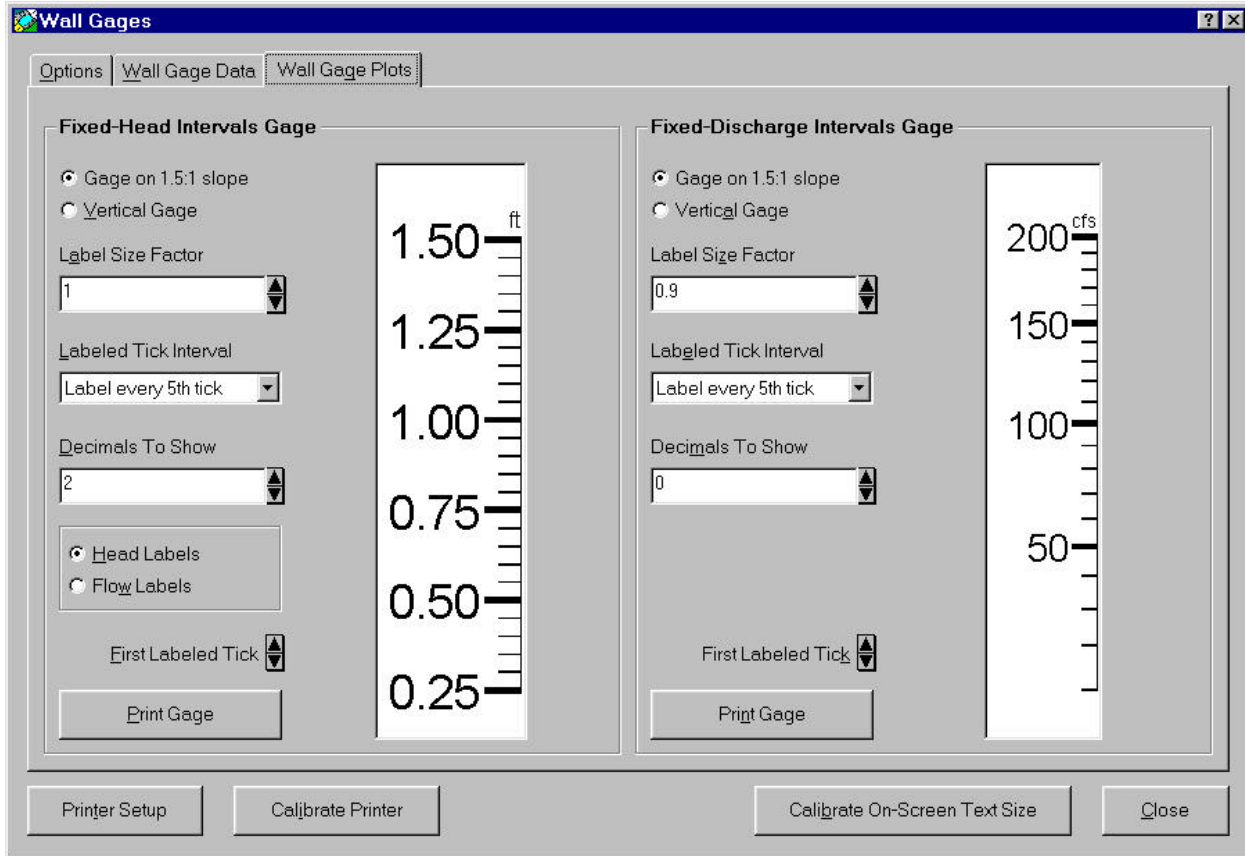

Figure 3. — Previewing Flume Wall Gages.

step approach to data entry, WinFlume provides a flume wizard. The wizard leads the user through the steps needed to enter the dimensions, hydraulic properties, and design requirements for a new or existing flume structure. The wizard explains each step of the process and gives instructions for completing each task. After completing the wizard steps, the user is free to use the design tools and output capabilities of the program as necessary for a particular application.

DESIGN OF LONG-THROATED FLUMES USING WINFLUME

The hydraulic design of a long-throated flume can be approached as a two step process. First, the throat section must be sized and the sill height determined, and then the lengths of the flume components are refined based on the selected throat geometry so that the structure meets the requirements of a long-throated flume. The design of the throat must satisfy six design criteria:

- Maintain user-specified freeboard in the approach channel at maximum flow.
- Maintain a Froude number of 0.5 or less in the approach channel at maximum flow.
- Maintain free-flow in the control section at maximum flow.
- Maintain free-flow in the control section at minimum flow.
- Meet user-specified target for flow measurement uncertainty at maximum flow.
- Meet user-specified target for flow measurement uncertainty at minimum flow.

The freeboard requirement is satisfied by reducing the contraction in the throat section shape, while the next three criteria are satisfied by increasing the contraction of flow in the throat section of the flume, either by raising the sill or narrowing the throat section. The last two criteria are satisfied by adjusting the throat section width at the base or top of the throat section so that enough sill-referenced head is generated upstream from the flume that it can be measured with a reasonable uncertainty. The total flow measurement uncertainty is obtained by combining the rating table uncertainty (typically about $\pm2\%$) with the uncertainty due to errors in head measurement. The magnitudes of most of the random errors affecting the head measurement are typically independent of the water level being measured. As a result, a flume with a narrow throat that creates a large head, h_1, will have a reduced percentage error in head measurement and a reduced combined flow measurement uncertainty.

WinFlume provides design review reports at several points within the program; these evaluate flume designs against the six design criteria and provide guidance to the user for modifying designs to meet the criteria. The user can manually adjust a flume design until each of the six criteria are satisfied, or the automated design module can be used to quickly determine the range of flume designs that satisfy the design criteria.

Automated Design Evaluation Module: WinFlume takes a dramatically different approach to assisted flume design than that used in FLUME 3.0. The older program used an iterative scheme to adjust the throat section geometry until a design was found that met the design criteria and satisfied a single user-specified head loss objective. Typical design objectives are to maximize or minimize head loss or obtain an intermediate head loss design. WinFlume's approach is to determine the range of throat section designs that yield workable flow measurement structures for the site, and then present all of these designs to the user, so that they may consider the advantages and disadvantages of choosing a structure with more or less head loss. This method has two advantages. First, the user who does not consciously verify a choice of head loss objective is not unknowingly steered toward a design that has little margin for tailwater or freeboard error (i.e., the minimum or maximum head loss design). Second, the program does not need to determine exactly how to modify the design to reach a particular head loss objective, which is a difficult optimization problem for some unusual flume configurations, such as those having circular throat sections. The WinFlume program simply analyzes a range of flume designs to determine those that are satisfactory. Designs having specific head loss characteristics are identified once this range is defined. This approach leads to a more robust design module.

Within the design evaluation module, the first four criteria are given primary importance, and the last two criteria (regarding flow measurement uncertainty) are considered secondary criteria, since a design that does not meet these criteria can be improved by simply selecting a better water level measurement method, without changing the design of the actual flume structure.

Using the Design Evaluation Module: To use the design evaluation module, the user chooses a method for adjusting the contraction in the throat of the flume (Fig. 4), and a dimensional increment for making those adjustments. This might be a minimum convenient dimensional increment for construction. The design algorithm brackets the range of possible designs using a subroutine that can determine the contraction required to produce a given upstream water level at maximum discharge. The maximum throat-section contraction will be that needed to produce a maximum upstream water level equal to the channel depth. The minimum contraction will be that which produces either an upstream Froude number of 0.5 at maximum discharge, or an upstream water level equal to the downstream tailwater at maximum discharge. Once the upper and lower contraction limits are identified, WinFlume evaluates all designs between those limits at the interval specified by the user. All designs that satisfy the four primary design criteria are presented to the user in a spreadsheet grid (Table 1). The user may select one of the designs to be the new current design, or discard the results of the analysis. Designs that have minimum head loss, maximum head loss, intermediate head loss, and head loss matching the bed drop at the site will all be listed in the output.
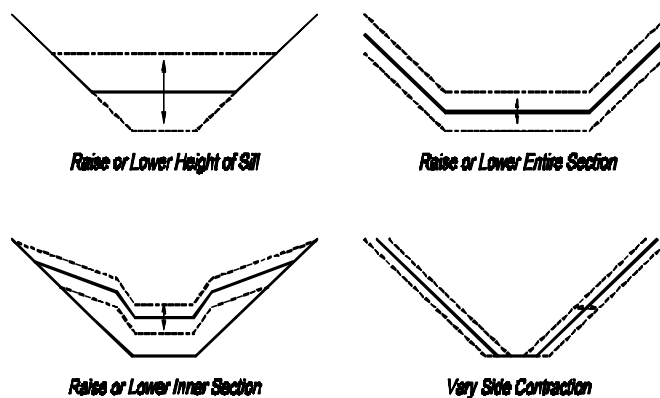

Figure 4. — Methods for Adjusting the Contraction of the Throat Section.

If the contraction increment specified by the user is too large, or if design criteria are too limiting, it is possible that no acceptable design will be found. If this occurs WinFlume will search for two adjacent designs for which all unsatisfied criteria in each of the designs are satisfied in the adjacent design. If such a situation can be found, then an acceptable design may exist between those two designs, and the analysis is repeated using a smaller increment of contraction change within that range. If no acceptable design is found, then all of the evaluated flumes are listed in the output, and the user can review the design reports on each to determine ways to relax the design criteria or change the initial structure to reach an acceptable design.

Two important columns of the design evaluation report (Table 1) are those labeled ***Extra Freeboard*** and ***Submergence Protection***. These columns illustrate the tradeoffs to be considered when comparing designs with more or less contraction, and respectively more or less head loss. Extra freeboard is the freeboard in the upstream channel *beyond that specified by the user as the design requirement*. The design having maximum head loss for a site will have zero extra freeboard. The submergence protection parameter is the difference between the computed maximum allowable tailwater level below the flume and the actual tailwater level at the site. Submergence protection can be considered a safety buffer indicating the amount of increase in tailwater that can occur before the flume becomes submerged. The design having maximum head loss for a site will have the largest submergence protection, while the design having minimum head loss will have zero submergence protection, unless the lower contraction limit is being controlled by one of the other design criteria, such as the approach channel Froude number.

Refining Flume Component Lengths: Once a satisfactory design for the throat section of the flume is obtained, the lengths of the approach channel, converging transition, control (throat) section, and diverging transition can be determined. The most direct method for refining these aspects of the design is the use of the abbreviated design review report located on the third tab in the lower right corner of the main WinFlume screen. As flume component lengths are modified, the design review report checks the length of each component against the design requirements and provides warning messages and suggested minimum or maximum lengths if the length of any component is not within the recommended range. Details regarding the recommended lengths of each flume component are given in the WinFlume help system and printed documentation, and several other long-throated flume references (e.g., Bos et al., 1984; Clemmens et al., 1993).

HOW TO OBTAIN WINFLUME

The WinFlume program was officially released in late 1999, and three minor upgrades have been released since that time. The current version is available on the Bureau of Reclamation's web site at http://www.usbr.gov/wrrl/winflume.

ACKNOWLEDGMENTS

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Table 1. — Example of Flume Design Alternatives Analyzed by the Design Module.

```
User: Wahl/Clemmens/Replogle          WinFlume32 - Version 1.02
D:\WinFlume\Source\Irrigation 2000 Example.Flm - Revision 13
Example flume for Irrigation 2000 paper
Design Alternatives Report, Printed: 3/1/2000 4:27:19 PM
-----------------------------------------------------------------------------------------------------------------------
                        <---------------- DESIGN CRITERIA --------------->         Actual  Actual   Extra
Control    Sill   Throat  <------- Primary Criteria ---------> < Secondary >   Head    Head   Froude Freeboard Submergence   Estimated
Section   Height  Width   Froude Freeboard Tailwater Tailwater Error   Error   Loss    Loss   Number  at Qmax  Protection Random Error
 Shape      ft     ft     Number at Qmax   at Qmax   at Qmin   @ Qmax @ Qmin  Comment   ft    @ Qmax    ft        ft       @ Qmax/Qmin
-----------------------------------------------------------------------------------------------------------------------
Trapezoid  3.852  21.255   Ok     Ok        Ok        Ok       Ok      Ok     Minimum   0.25   0.13     0.96      0.00      ±1.91-1.99%
Trapezoid  4.     21.7     Ok     Ok        Ok        Ok       Ok      Ok      ---      0.37   0.12     0.83      0.13      ±1.91-1.99%
Trapezoid  4.25   22.45    Ok     Ok        Ok        Ok       Ok      Ok      ---      0.59   0.12     0.62      0.34      ±1.91-1.99%
Trapezoid  4.414  22.942   Ok     Ok        Ok        Ok       Ok      Ok   Intermediate 0.73  0.11     0.49      0.48      ±1.91-1.99%
Trapezoid  4.5    23.2     Ok     Ok        Ok        Ok       Ok      Ok      ---      0.81   0.11     0.41      0.55      ±1.91-2.00%
Trapezoid  4.75   23.95    Ok     Ok        Ok        Ok       Ok      Ok      ---      1.03   0.10     0.20      0.77      ±1.91-2.00%
Trapezoid  4.984  24.653   Ok     Ok        Ok        Ok       Ok      Ok     Maximum   1.23   0.10     0.00      0.97      ±1.91-2.00%

Method of Contraction Change = Raise or Lower Sill Height
Evaluation Increment = 0.25 feet
```