FLUME
Design and Calibration of Long-Throated Measuring Flumes

Version 3.0

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Version 1.* 1984, Bos, M.G., J.A. Replogle, and A.J. Clemmens, Flow Measuring Flumes for Open Channel Systems, Wiley, New York, U.S.A.

Version 2.* 1987, Clemmens, A.J., J.A. Replogle, and M.G. Bos, Flume: A Computer Model for Estimating Flow through Long-Throated Measuring Flumes, U.S. Department of Agriculture, ARS-57, Springfield, VA, U.S.A.

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Abstract

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A mathematical model has been developed for designing a flow-measuring structure in any open channel under user-given hydraulic boundary conditions. Upon completion of the design, the model will compute the head-versus-discharge relation and the hydraulic energy losses for the flume or weir. The computer program presented in this publication can accommodate a wide variety of structure and channel shapes as well as many different input and output units. This version greatly expands the previously published programs.

Key words
broad-crested weirs, computer modelling, design, flow measurement, flumes, hydraulics, open-channel flow, discharge rating.

Preface

To effectively accomplish surface-water management for irrigation distribution, municipal supply and treatment, watershed hydrology, flood-flow monitoring, or other purposes, it is important that the flow rate be accurately measured. Increasing and competing demands for water in our society are making efficient water use ever more necessary.

As a general policy, we recommend that water-measuring capability be included in all new water projects and that existing water projects be retro-fitted for water measurement as soon as practical.

Usually water measurements should be planned at all points where it can be reasonably established that information on the flow rate will affect management decisions. Thus water measurements should be planned at all bifurcations or divisions in flow within a distribution canal system, at all delivery outlets, and in the stream or river from which water is diverted.

For most open-channel flow measurements, we recommend 'long-throated critical-depth flow-measuring flumes', often shortened to 'long-throated flumes'. Broad-crested weirs with a streamlined flow contraction also fall into the long-throated flume family. Broad-crested weirs are particularly well adapted to irrigation canals. Flumes are better adapted to natural streams. The application of this family of long-throated flumes and broad-crested weirs is unlimited. They should greatly contribute to the effective management of one of the earth's most widely needed resources: water.

FLUME is a computer program for assisting in the design of long-throated flumes (broad-crested weirs) and for predicting the flow rate through the structure being designed in the user-given channel. FLUME Version 3.0 was developed for computers which operate under the MS-DOS environment.

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1 Introduction

1.1 History and Advantages

Critical-flow devices are often used to measure flow in open channels. Most of these devices require laboratory calibrations because the discharge is not theoretically predictable, except through empirically derived coefficients. Two flow devices whose discharges can be theoretically predicted without the need for such coefficients are the long-throated flume and the modified broad-crested weir. Both have similar hydraulic properties.

The model for predicting discharge through long-throated flumes has resulted from over a century of development. The first laboratory and theoretical studies on critical-depth flumes were made by Belanger in 1849 and by Bazin in 1896. These studies were extended by Crump (see Ackers et al. 1978 and Inglis 1928), Jameson (1930), Fane (1927), Palmer and Bowlus (1936), and others in the early part of this century. The theory and dimensional requirements for these flumes were well known by the 1950's (Wells and Gotaas 1958); nevertheless, calibration still required an empirical discharge coefficient. Theoretical predictions of flow were investigated by Ackers and Harrison (1963) and further refined by Replogle (1975). The stage-discharge theory of the current model is essentially that presented by Replogle, with minor improvements. Bos (1989) and Bos and Reinink (1981) developed a procedure for determining the required head loss across these flumes. This general theory was incorporated into the current model, with minor modifications to make it consistent with the procedures for the stage-discharge computations. This model has been developed to assist users in designing a flow-measuring structure in an arbitrarily shaped canal. It also supplies a complete prediction of flow patterns (head-discharge relationship and required head loss) through long-throated, critical-flow flumes and weirs.

These flumes and weirs have a number of advantages:

- Provided that critical flow occurs in the throat, a rating table can be calculated with an error of less than 2% in the listed discharge. The calculation can be made for any combination of a prismatic throat and an arbitrarily shaped approach channel;
- The throat, perpendicular to the direction of flow, can be shaped in such a way that the complete range of discharges can be measured accurately;
- The required head loss over the weir or flume is minimal to ensure a unique relationship between the upstream sill-referenced head, h_1, and the discharge, Q;
- This head-loss requirement can be estimated with sufficient accuracy for any of these structures placed in an arbitrary channel;
- Because of their gradually converging transition, these structures have virtually no problem with floating debris;
- Field observations and laboratory tests have shown that the structure can be designed to pass sediment transported by channels that have subcritical flow. However, sedimentation can be a problem when sediment loads are excessively high

or when the flume causes a significant reduction in the flow velocity in the approach channel;
- Provided that the throat is horizontal in the direction of flow, a rating table can be produced which is based upon post-construction dimensions. Thus, an accurate rating table can be produced even if the flume is not constructed to the designed dimensions. Also, the throat may be reshaped as needed according to changing site conditions;
- Under similar hydraulic and other boundary conditions, these weirs/flumes are usually the most economical of all structures for accurately measuring open-channel flows, provided that conditions are such that a weir/flume is feasible.

Because of the above advantages, these flumes and weirs are useful for many flow-measurement applications, particularly when the structure must have a minimal impact on existing flow and water-surface elevations.

1.2 Description

Long-throated flumes generally consist of five parts as shown in Figure 1.1:
- An approach channel, where the flow is stable and uniform so that the water level (and thus the energy head) can be determined accurately. The approach channel may be lined as shown in Figure 1.1 or may be the original earthen channel;
- A converging transition that provides a smooth acceleration of flow with no discontinuities or flow separation. The transition may consist of plane surfaces or may be rounded;
- A throat, where the flow is accelerated to critical flow. In the direction of flow, the throat must be horizontal. Perpendicular to the flow, any shape can be used;
- A diverging transition to reduce the flow to an acceptable subcritical velocity and to recover head. If no head needs to be recovered an abrupt transition can be used;

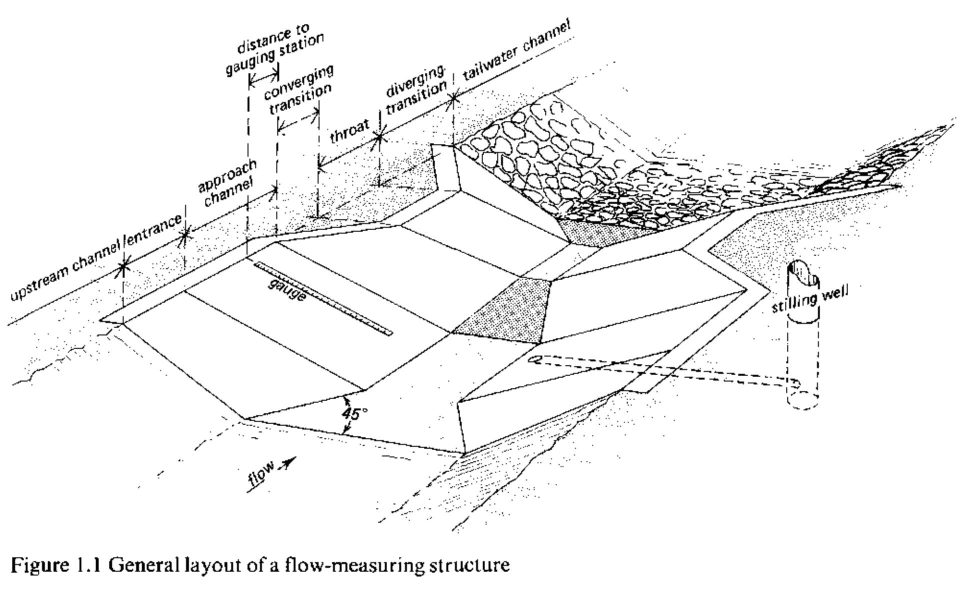

Figure 1.1 General layout of a flow-measuring structure

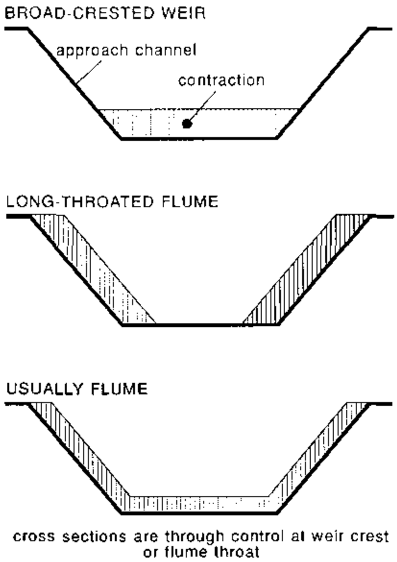

Figure 1.2 Distinction between a weir and a flume

- A tailwater channel where the water level is controlled by the flow downstream and the hydraulic properties of the tailwater channel. A knowledge of this downstream water level is important to determine the proper elevation of the flume throat.

The major differences between long-throated flumes and broad-crested weirs stem from the historical use of terminology rather than from hydraulic properties. In this publication, both are considered long-throated flumes. The historical distinctions are shown in Figure 1.2.

In general, both types of measuring structure cause a constriction in the flow area. The design of these structures is based on providing enough of a constriction to produce critical flow over the full range of expected discharges while not producing too much head loss between the upstream water level and the tailwater level.

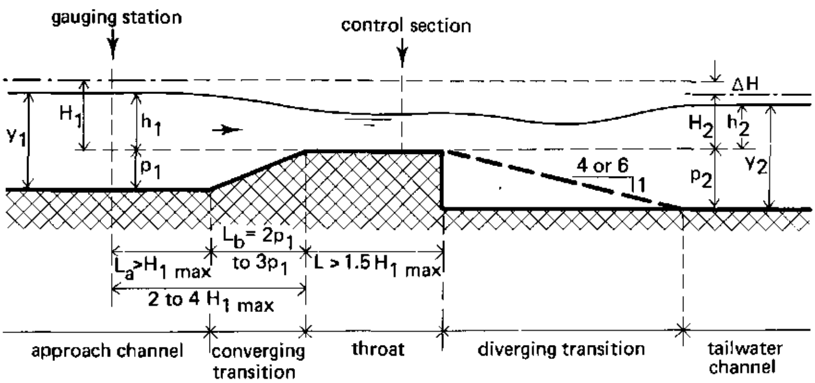

Figure 1.3 Profile of flow through a long-throated flume

Figure 1.3 shows the general profile of flow through a long-throated flume. The subscripts 1 and 2 refer to conditions in the approach and tailwater channels, respectively. The reference elevation for energy levels is the bottom of the flume throat or crest of the weir sill, which will be referred to as the 'sill reference'. Thus, as shown, the actual water depth is described by y, and the sill-referenced head by h. The difference between the two is the sill height, p. Also shown is the energy level, H, and the energy loss across the flume, ΔH.

The control section is the approximate location of critical flow within the flume throat. The gauging (or head-measurement) station is the location within the approach channel where the upstream head is measured. For critical-flow devices, there is a unique relationship between the upstream head and the discharge.

As mentioned in the description of Figure 1.1, the five parts of the channel and structure may have different shapes and sizes. As a result, the visual appearance of actual structures differs widely depending on the function, size, and construction material of the flume or weir. Figures 1.4 through 1.10 give some examples of flumes.

1.3 Selecting a Site

All structures for measuring or regulating the rate of flow should be located in a channel reach where an accurate value of h_1 can be measured and where sufficient head loss can be created to obtain a unique Q-versus-h_1 relation (modular flow). The

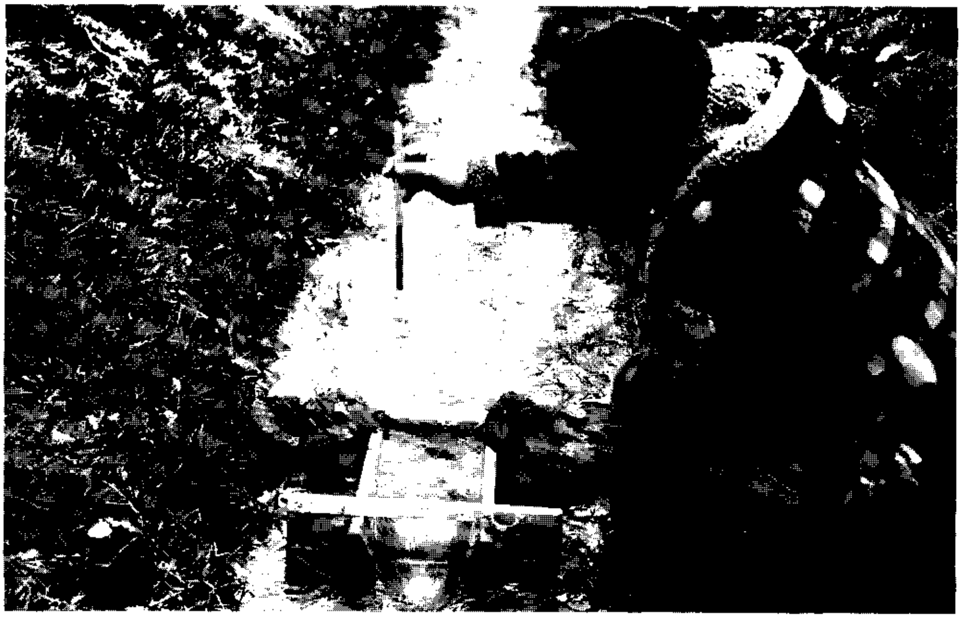

Figure 1.4 Portable RBC flume to measure flow in small drains, small earthen irrigation canals, or in furrows. This sheet-steel flume measures up to 9 l/s. The flume can also be constructed from pvc or marine plywood. If another size and/or shape is used, the maximum capacity of the portable version of the flume can be as high as 150 l/s.

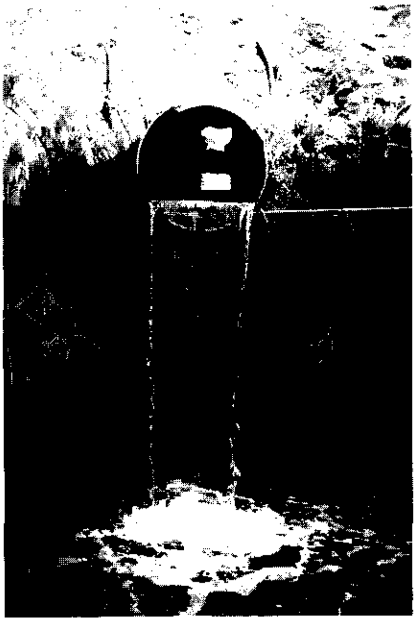

Figure 1.5 An 0.15 m high sill in an 0.60 m diameter pipe is used to measure tail flow from an irrigation lateral into a drainage canal. The control section can also be triangular or trapezoidal to measure low flows more accurately.

Figure 1.6 This 15.45 m wide flume has a throat length of 3.05 m. At its design capacity of 56.6 m^3/s, a head loss of only 0.12 m is required for flow to be modular. On large structures, a 1-to-6 downstream ramp reduces construction cost. Low crests (< 0.5 m) often have a vertical downstream face.

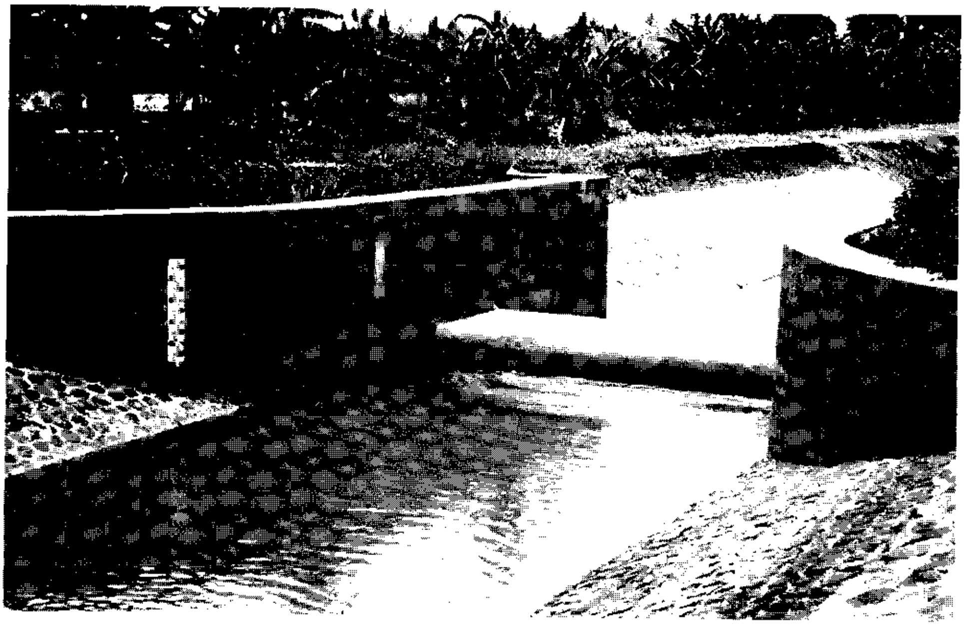

Figure 1.7 This rectangular flume in an unlined channel was constructed of masonry. All five flume parts are contained within the rectangular, lined section. The contraction was made with a bottom sill.

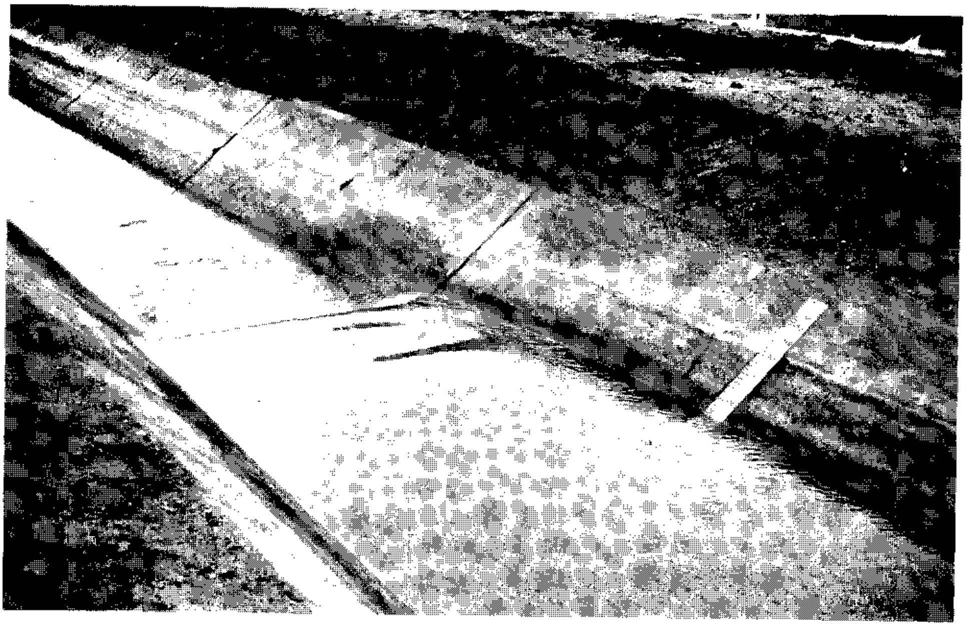

Figure 1.8 This flume was constructed by adding a bottom sill to an existing lined canal. The canal lining makes up part of the throat and the other four parts of the flume. This style is often called a Replogle flume.

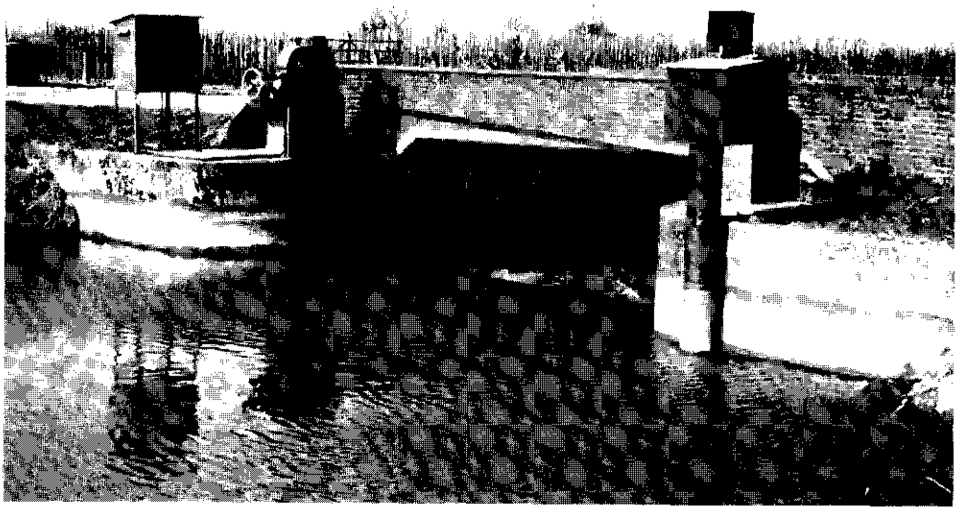

Figure 1.9 A broad-crested weir with movable crest can be used to regulate and measure the flow into a canal. This combination of functions facilitates the control of irrigation water.

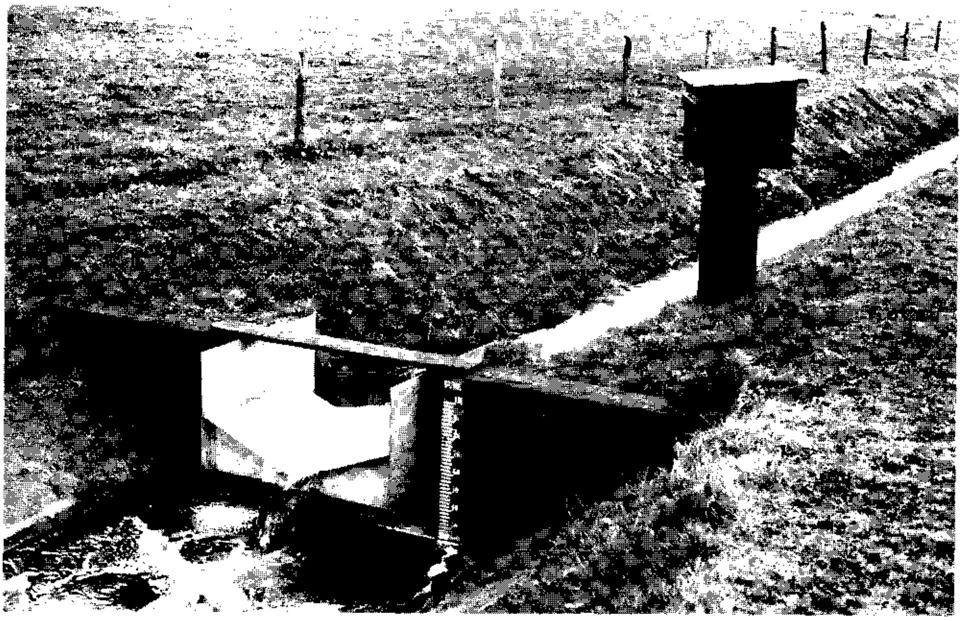

Figure 1.10 In soils with a low bearing capacity, wooden sheet piling can support a metal broad-crested weir.

survey of a channel to find a suitable location for a structure should also provide information on the following relevant factors that influence the performance of a future structure:

- Upstream of the potential site, the channel should be straight and have a reasonably uniform cross-section for a length equal to approximately ten times its average width. If there is a bend closer to the structure, the water elevations at the two sides of the channel will be different. Reasonably accurate measurements can be made (added error about 3%) if the upstream straight channel has a length equal to about two times its width. In this case, the water level should be measured at the inner bend of the channel;
- The channel reach should have a stable bottom elevation. In some channel reaches, sedimentation occurs in the dry season or in dry periods. These sediments may be eroded again during the wet season. Such sedimentation changes the approach velocity towards the structure or may even bury the structure, while erosion may undercut the foundation of the structure;
- Whether the water level in the channel is directly predictable by the channel discharge, or whether it is influenced by downstream confluences with other channels, operation of gates, reservoir operation, and so on, must be determined. The channel water levels greatly influence the amount of contraction needed to obtain modular flow;
- Based on the channel water levels and the required sill height in combination with the Q-versus-h_1 relation of the structure, the possible innundation of upstream surroundings should be studied. These inundations usually cause sedimentation because of the subsequent change in the approach-flow conditions. An excessive change in upstream water level after flume installation may also limit the amount of flow that is able to enter the canal from its source;
- The Froude number, Fr_1, at the gauging station is defined as

$$Fr_1 = \frac{v_1}{\sqrt{\frac{g\,A_1}{B_1}}} \qquad (1.1)$$

  where v_1 is the average flow velocity at the gauging station, g is the acceleration due to gravity, A_1 is the cross-sectional area perpendicular to the flow, and B_1 is the water-surface width at the gauging station. To obtain a reasonably smooth water surface for which the elevation can be determined accurately, the Froude number, Fr_1, should not exceed 0.5 over a distance of at least thirty times h_1 upstream from the structure. If feasible, we recommend reducing the Froude number to 0.2. For channels with high sediment loads, the Froude number should be kept high;
- Subsoil conditions: at the site of the structure, leakage around and beneath it due to the head loss over the structure must be cut off at reasonable costs. Also, a stable foundation, without significant settling, must be secured;
- To avoid sedimentation upstream of the structure, sufficient head must be available in the selected channel reach. For more details, see Section 4.5.

2 Getting Started

2.1 Installation

You should have received one 3.5 inch disk with FLUME 3.0. The disk contains the packed executable program plus the overlay files and the configuration files that are required to run FLUME. The floppy also contains a sample database of flume designs.

FLUME operates in the MS-DOS 3.3 or later environment. Version 3.0 requires about 520 Kb of free memory. A hard disk drive is required, an 80286 microprocessor or higher is recommended, and a math-coprocessor is optional, but highly recommended.

Hard disk system

To install FLUME on a hard-disk system (e.g. on Drive C):

1 Insert the disk in the A Drive, type **a:** (or **b:** if you use the B Drive), and hit **enter**.

2 Type **instflm** and hit **enter** again.

The program now creates a sub-directory FLUME on Drive C (C:\FLUME), and subsequently unpacks the files. Messages appear on-screen to show the installation progress. If your computer already has a sub-directory C:\FLUME, existing files may be lost. You will be asked 'Do you want to proceed with the installation? Yes/No'

To run FLUME from a hard-disk system (C Drive):

1 Move to the C: directory C:\>.

1 Go to the flume directory C:\FLUME>. To go here, type **cd\flume** and hit **enter**.

2 To execute the program; type **flm** and hit **enter**. If you use FLUME on a monochrome (non-color) monitor with a color video card (e.g. some portable computers), you must type **flm m** to set FLUME for that monitor. This is only necessary the first time you run FLUME on that monitor. The video setting can be altered manually (Section 2.2.2).

Upon typing **flm** (or **flm m**), three introductory screens will precede the main menu of FLUME. Pressing any key will advance these screens more quickly. This main menu consists of five branches:

MAIN MENU FLUME SYSTEM

SELECT FLUME | EDIT FLUME DATA | DESIGN FLUME | REPORTS/GRAPHS | OPTIONS

The **Select Flume** branch will be treated in Section 2.4 and the **Options** branch in Sections 2.2 and 2.3. The other branches will be treated in Chapter 3. The menu structure and general procedure to move through the menu is described in Section 2.5.

2.2 Initial Settings

When you enter the program for the first time, you need to tell FLUME in what units system you would like to work and what kind of printer you have. The procedure for this is as follows:

1 Move the cursor to the **Options** menu choice with the arrow keys.
2 Hit **enter**.

The screen display then shows:

MAIN MENU F L U M E SYSTEM

SELECT FLUME EDIT FLUME DATA DESIGN FLUME REPORTS/GRAPHS OPTIONS

Save flume data
Delete flume
Make backup
Read backup
Files repair
Units setting
System settings
Printer setting

The first five sub-menu options relate to database handling and are covered in Section 2.4. The last three options should be considered before FLUME is used. Hence:

3 Move the cursor to the **Units setting** menu choice with the **arrow** keys.
4 Hit **enter**.

2.2.1 Units Setting

Under **Units setting**, you can enter units for flume dimensions and head values, discharge values, and velocities. These can be changed at any time, and the program will simply convert all dimensions to the new units. The screen will display:

Set the unit for lengths and heights	m	meters
Set the unit for discharge figures	m^3/s	cubic meters per second
Set the unit for water velocity	m/s	meters per second

The currently selected units are shown. The procedure to change the units is:

1 Use **arrow** keys to make a selection if length, discharge, or velocity units need to be changed.
2 Hit **enter**. The above double-lined window will disappear, and be replaced by a new window containing the available units.

Depending on the above selection, the following unit options will be available:

length unit

m	meters
mm	millimeters
ft	feet
in	inch

discharge unit

m^3/s	cubic meters per second
l/s	liters per second
cfs	cubic feet per second
gpm	U.S. gallons per minute
acft/hr	acre feet per hour
MI	miner's inches, Arizona (1 cfs = 40 MI)
Dm^3/hr	cubic decameter (Megaliter) per hour
Mgd	million U.S. gallons per day

velocity unit

m/s	meters per second
ft/s	feet per second

3 Use the **arrow** keys to select the desired units.
4 Hit **enter**. The (newly) selected units will be shown to the right of the menu window.

To leave this sub-menu and return to the next higher menu level, you have to hit the **Esc** key. A message will be given that the new units are saved.

2.2.2 System Settings

You can enter this menu branch again by using the arrow and enter keys. The following menu window, plus selected options, will appear on-screen:

Set a beep to accompany messages?	**Yes**
Set duration of message (1 to 9)	**5** seconds message display
Set lines per page (12 inch = 72)	**72** lines per full printed page
Enter user name	**Joseph Engineer, MSc**
Set screen mode	**Color** Mono/LCD VGA

To change these, if need be:

1 Use **arrow** keys to move menu bar (highlighted) to the option to be changed.
2 Hit **enter**. The above window will disappear and a new double-lined window will be shown.
3 Select/type new value or name using **arrow** keys.
4 Hit **enter**.

Upon hitting the **Esc** key, the message 'New settings are saved' is given according to the selected options.

We recommend setting a beep to indicate that FLUME is providing you with information. Messages from FLUME will be displayed for the duration that you have selected. If any key is hit, the message will disappear more quickly.

We also recommend that you enter your name when using FLUME, since that name appears on all output reports.

FLUME automatically detects the type of graphical interface card your computer has. However, it is not possible to detect the presence of a monochrome monitor used with a color graphics card. To obtain a proper screen output setting, you then should use the 'set screen' mode.

FLUME can be used with Hercules, CGA, EGA, or VGA graphic cards. You should select the proper combination of printer and video.

2.2.3 Printer Setting

Under this menu option, you can select from a variety of printers. Following the same procedure as above, you will obtain a window showing:

PRINTER MAKE	MODEL	VIDEO
Epson	FX	CGA – EGA – VGA
Epson	SQ 24-PIN	CGA – EGA – VGA
Etc.		

Not all makes and models of printers are available. If your printer is not listed, you may have to do some experimenting to find a printer selection that will give you good graphical output. Text output is usually not a problem.

2.3 Database Handling

FLUME maintains a database of flume designs and rating tables. These databases are stored in DBASE III format and can be accessed through DBASE III, CLIPPER, and other MS-DOS programs that read DBASE III formats. The FLUME database contains information on the site where each flume is located, the user demands on the structure, and on the structural dimensions of each flume. Rating tables are stored in individual databases for each flume. As mentioned in Section 2.2, database handling is located under the **Options** branch of the main menu. Here, five sub-menus are available: **Save flume data**, **Delete flume**, **Make backup**, **Read backup**, and **Files repair**.

FLUME keeps track of the version number for a particular flume. This is to help the user match up reports on flume designs and dimensions with the calculated rating tables and graphs. Each time the flume data is saved, the version number is increased by 1. However, it is possible to alter the flume dimensions after a rating table has been printed and print out a flume data report which does not match the rating table, even though they have the same version number. This problem can be avoided by saving the flume data after any editing of dimensions and prior to writing any reports.

2.3.1 Save Flume Data

While working on a flume design, you may want to save all the data you entered before altering the dimensions with the design procedures (e.g. before using the **Design Calculations** sub-menu). To do this:

1 Select the **save flume data** option.
2 Hit **enter**.

In the process, all new data will be written over the previous data on the flume with the same database name. You are also given the option to save the current flume data if you want to work on another flume from the database, or if you want to return to MS-DOS. On-screen, the question is framed:

Do you want to save the data on the current flume ? **Yes** No

1 Select Yes or No by using the **arrow** keys.
2 Hit **enter**.

2.3.2 Delete Flume

Upon entering this menu option, you will be shown the following window

Delete from your hard disk or from a backup disk? **hard disk** backup disk

Once a disk is chosen, the following menu appears listing all flumes in the database.

```
═══ SELECT FLUMES THAT YOU WANT TO DELETE ═══
 Flume name          Description
 etc.

═ ENTER = select flume ═ DEL = un-select flume ═ ESC = stop selection ═
```

To delete all data on a flume:

1 Select a flume for which information is to be deleted using the **arrow** keys. Please note that FLUME does not allow you to delete the flume on which you are currently working.
2 Hit **enter**.
3 Move to next flume for which data are to be deleted, by repeating steps 1 and 2.
4 Hit **Esc** and read warning/question on-screen and toggle Yes or **No** using the **arrow** keys (No deleting is default option).
5 Hit **enter**.

2.3.3 Make Backup

FLUME keeps track of a database containing saved flume designs. If you choose **Make backup** under the **OPTIONS** menu, FLUME will ask you whether the backup is to be made on the A or B Drive. If no backup file exists, FLUME will ask whether a backup is to be created. The backup procedure is:

1 Insert formatted disk in either Drive A or B.
2 Toggle to the appropriate A or B-drive and hit **enter**.

If you inserted a disk that contains no earlier prepared FLUME database with backup files, the program will ask:

This disk has no FLUME backup file. Do you want to make one?

Yes No

3 If you answer No, a warning will appear on-screen. You can replace the disk with another disk on which you have previously made a backup, or change your response to Yes. If you answer Yes, a FLUME backup file will be created and FLUME will display the list of flumes in the active database.

```
═ SELECT FLUMES THAT YOU WANT TO COPY TO BACKUP-DATABASES ═
  Flume name          Description
  etc.

═ ENTER = select flume ═ DEL = un-select flume ═ ESC = stop selection ═
```

4 Select a flume by using the **arrow** keys.
5 Hit **enter**.
6 Move to next flume and repeat Steps 4 and 5.
7 Hitting the **Esc** key will return you to the **OPTIONS** menu system.

FLUME backs up the channel site and flume dimensional data and rating tables. You will be given a message that a backup has been made.

2.3.4 Read Backup

Data on the channel and flume demensions stored on a backup disk can be read into the FLUME database through the **Read backup** sub-menu. The steps to be followed are:

1 Answer A or B to the question 'Which drive do you want to use for backup?'
Note: If you hit **enter** before the backup disk is in the drive, a warning will be given.

FLUME will display:

```
SELECT FLUMES THAT YOU WANT TO COPY FROM BACKUP-DATABASES
Flume name          Description
etc.

ENTER = select flume == DEL = un-select flume == ESC = stop selection
```

2 Select those flume files that are to be read into the database by using the **arrow** keys.
3 Hit **enter**.

If you try to read a 'flume name' into the database, while the database already contains data on a flume with this name, you will be asked; 'Do you want to overwrite the data in the FLUME database?' If you toggle to Yes and hit **enter**, you will lose the old database data. (Note: you may want to copy the existing flume to a new name before overwriting it.)

4 Hitting the **Esc** key will return you to the **Options** menu system. A message will be given that the backup was read.
A second hit on the **Esc** key brings you back to the main menu.

A backup flume database is essentially identical to the flume database file in use. Thus the **Read backup** option can be used to merge files from separate flume databases, or to move flume data from one machine to another. The **Make backup** option should always be used to read additional flumes into the database.

To make an initial backup, or to merge databases from two computers, you should **not** use MS-DOS to copy all *.DBF files to an empty floppy disk. FLUME only recognizes *.DBF files that are within a FLUME database!

2.3.5 Files Repair

This option allows you to check whether all needed system files are available in the flume directory. It also checks all data files and makes repairs if needed and possible. If you hit the **enter** key, message(s) will be given on missing system files, followed by a message on database file repair. The entire procedure is automatically performed by the program.

2.4 Select Flume

When you start FLUME, you must first select a flume with which to work before any other data can be entered. If you attempt to select any of the other menu branches except **Select flume** or **Options** before selecting a flume, FLUME will require you to select a flume first. When you start FLUME by entering flm (or flm m), the **Select flume** branch of the menu will be highlighted. Hitting **enter** will show the following window on screen:

```
SELECT A FLUME
Create a new flume - with default data
Create a new flume - copied from existing flume
Flume name          Description
etc
```

A database of an example flume is included with FLUME. If for some reason no existing database file (named Flm.DBF) is available, the only options you have are to **Create a new flume – with default data**, or to read flumes from a backup disk and then select one of those flumes.

2.4.1 Create a New Flume – with Default Data

There are many situations where you will want to design and build a one-of-a-kind flume. This is particularly true for larger irrigation canals and for natural streams or drains. Equally, there are many situations where a calibration is needed based on the 'as-built'dimensions of the existing (empty) structure. You should then;

1 Select the **create a new flume – with default data** sub-menu option.
2 Hit **enter**.
3 Type name of new flume (up to 8 characters long).
4 Hit **enter**.
5 Type a description of the new flume (up to 48 characters long).
6 Hit **enter**

This will return you to the main menu with the short name of the selected flume shown at the bottom of the screen. The short name is used to store all the data on the canal site and on the structure in the flume database (*.DBF file) while the flume description provides more space for easy identification of the flume and site.

A new flume will contain default values for the flume dimensions and canal/design data. You should follow through the **Design flume** branch or the **Edit flume data** branch to change this data to match the conditions for the new flume and be sure that all data are correct.

2.4.2 Create a New Flume – Copied from Existing Flume

In irrigation districts, it is useful to standardize on standard-sized structures. In this case, rather than a custom design, you will simply want to check the suitability of a standard structure at the proposed site. To do this, you **Copy (data) from (an) existing flume**, in this case the standard structure, to the new flume/site. This will copy the flume dimensions plus design or site information contained in the database for that flume. The steps are:

1 Select the **Create a new flume – copied from existing flume** sub-menu option.
2 Hit **enter**.
3 Type name of the new flume.
4 Hit **enter**.
5 Type a description of the new flume.
6 Hit **enter**.

All names of structures in the flume database will be shown on-screen as follows:

```
SELECT A FLUME TO COPY DATA FROM
Flume name          Description
etc
```

7 Use the **arrow** keys to move through the listed flumes, and
8 Hit **enter** to copy all data of the selected combination of canal and flume to the 'new flume'.

You will now be back in the main menu with the new flume selected for use.

2.4.3 Select Existing Flume

For any structure that has been entered into the database, whether from custom design, user entry of 'as-built' conditions, or selection of a standard structure, FLUME can be used to generate a new version. For this purpose, data on the structure must be retrieved from the database. The procedure is:

1 Select the name of the flume you want by using the **arrow** keys.
2 Hit **enter**.

This brings you back to the main menu with the flume you have selected for use.

2.5 FLUME Menu System Basics

The FLUME menu system is written in CLIPPER, a compiled database language which uses DBASE III syntax. Most of the numerical computations are made with Microsoft C. The menus are set up in a hierarchical format, as shown by the menu system outline in Figure 2.1.

Navigating through FLUME is fairly simple once you have done it a few times. We recommend that you go through the menu options a few times with a test flume just to get the feel of the program.

At any level within the menu system, you choose the different menu options by either pressing the **arrow** keys until the desired option is highlighted and then pressing **Enter**, or by pressing the first letter of the option (e.g. pressing **d** gives menu option **Design flume**). There are two types of menu layout. The options can be given horizontally across the screen (as for the main menu) or vertically below a horizontal menu option. For the horizontal menus, the left and up **arrow** keys move you to the left, while the right and down **arrow** keys move you to the right. For the vertical menus, the left and up **arrow** keys move you up while the right and down **arrow** keys move you down. When a menu has more than one option starting with the same letter, pressing that letter gives the first menu option starting with that letter. The **Esc** (escape) key moves you from the menu you are on to the next menu level up. From the main menu, **Esc** starts the procedure for exiting FLUME and returns you back to DOS.

There are two or three menu levels as shown in Figure 2.1, depending upon which menu options you choose. Below these menu options, you will be asked for information, which can be text, numbers, or the selection from a table of choices. Tables of choices are slightly different from menus in that the choices are surrounded by a double-lined box. Choices result in data entry into the database of flume information or settings, while menu item selections do not.

2.6 Data Entry

2.6.1 General Data Entry

For text and numeric data entry on the choices in a double-lined window, the general situation is;

1 Use the **arrow** keys to highlight the line on which data are to be entered.
2 Press the **enter** key to move to the field. The first double-lined window will disappear, and be replaced by a new window showing either which data should be entered or the available options from which you can select.
3 Enter the data or select from a new choice.
4 Then press the **enter** key again to record the information.

Most numeric data have an allowable range of values. If you input a value that is out of range, FLUME will return you to the data entry location after you hit **enter**, and will continue to do so until you either enter a value that is within range, or hit **Esc**. The latter returns the field to the previously saved value.

For some mid-level menus, the menus are simply shown below the higher level menu.

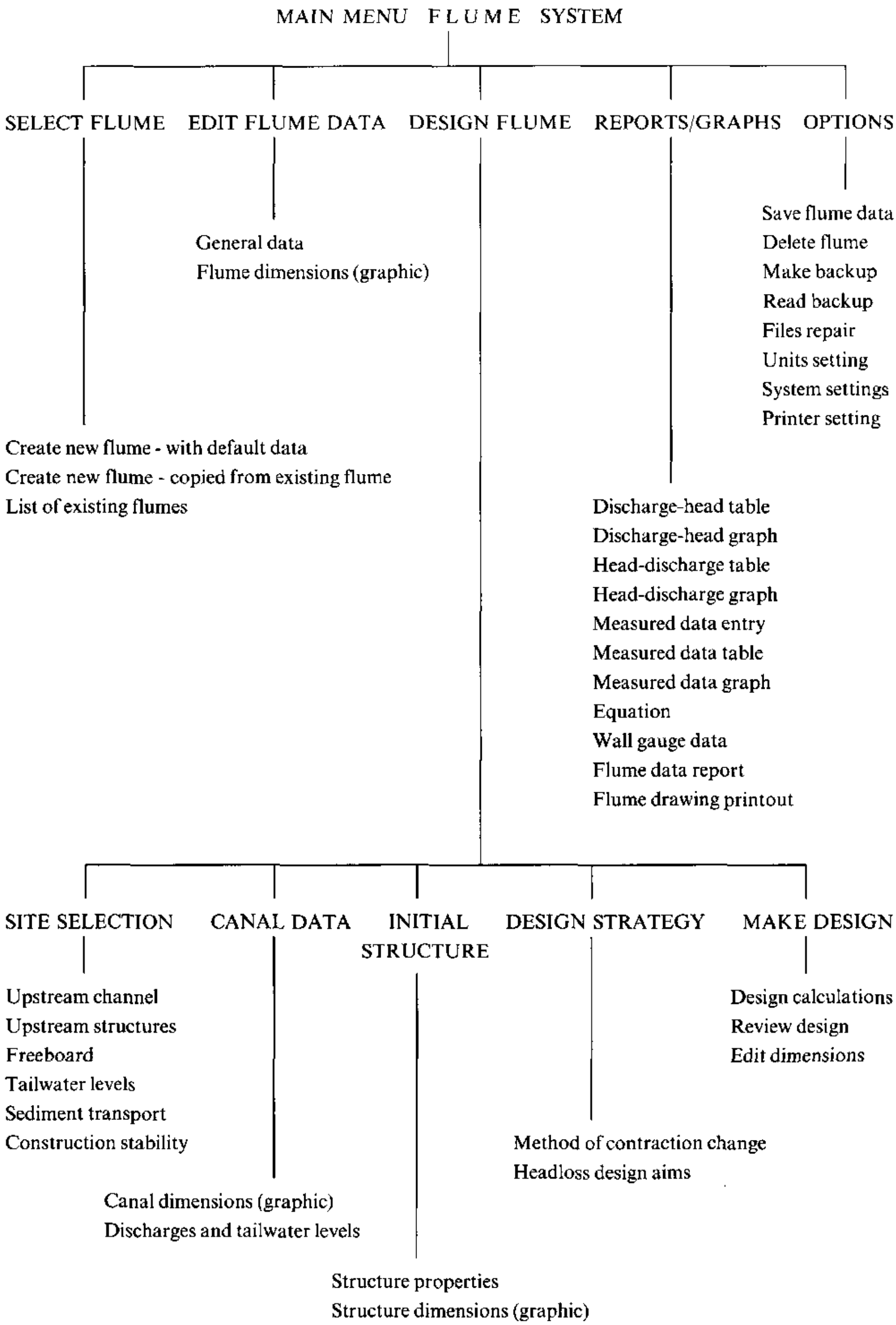

Figure 2.1 The FLUME program menu system outline

For others, no higher level menus are shown. This is dictated by the space limits on the screen and the desire to make the system as easy to use as possible. For some lower level menus, the data relevant to the menu choices are given on the screen below the menus. This is to aid you in deciding which menu choices need to be selected, if any (i.e. according to what data have to be modified).

For some menu choices requiring data input, you may enter data manually or press the **F1** or **F4** key to select from a list of options. Such 'help' menus are available for such things as Manning roughness, absolute roughness height, and precision of head detection method. To use the 'help' menu, the above Steps 3 and 4 are replaced by:

3 Hit **F1** or **F4**.
4 Use the **arrow** keys to select the relevant option.
5 Hit **enter**. The selected value/option will be shown next to the first double-lined window.

At the bottom of the screen, the name of the flume being used is given. Below that is a more detailed description of the current menu item highlighted. This allows FLUME to keep the menu selections to one or two words while still providing some detail about what the menu choices represent.

When new data are entered into the database on exiting a sub-menu, a message is given at the bottom of the screen indicating that these data have been saved.

2.6.2 Graphic Data Entry

Graphic data entry is somewhat different from the standard text and numeric data entry. The **Graphic data entry** screen is used at four places in FLUME to enter or edit data; three times under the **DESIGN FLUME** branch to enter **Canal dimensions**, **Structure dimensions**, and to **Edit dimensions** of the designed structure, and one time to enter **Flume dimensions** under the **EDIT FLUME DATA** branch (Figure 2.1). At first glance, all graphic data entry screens are similar. However, the menu options shown at the upper right corner are different for each screen.

All current data and dimensions of the selected flume are shown on the graphic screen. To alter these data:

1 Use the **arrow** keys to move to a menu bar.
2 Press the **Enter** key to select the option desired.

For the **Edit bottom profile** option,

3 The **arrow** key moves the highlighted block only between those flume parts that can be altered. (This is just like a sub-menu except that letter keys do not work to select item.)
4 Upon hitting **enter**, the dimensions under this flume part will also be highlighted.
5 Type new dimensions and hit **enter** again. The graphic screen will be redrawn to the new dimensions.
6 Repeat Steps 3 through 5 for other data to be changed.
7 Hit **Esc** to return to the menu at the upper right corner of the screen.

For some data entry screens, certain data cannot be altered and are not accessible. Other data are calculated and are provided for information only.

When you choose one of the **Edit cross-section** options, a new menu is shown which allows you to select the cross-section shape (move by using **arrow** keys and hit **enter**). Once this has been chosen, the next sub-menu (in graphics form) allows you to alter the cross-section dimensions sequentially. Each cross-section is edited separately.

In addition, there are two options to show the channel and control cross-sections superimposed on one another. This allows you to see whether the basic data have been entered correctly.

2.6.3 Measured Data Entry

FLUME has a special format for entering field or laboratory data which are to be compared with the theory from FLUME (see **Measured data entry** under the main menu branch **REPORTS/GRAPHS**). Here numeric values are typed, followed by hitting the **enter** key. The **arrow** key moves you from one field to another. On initial entry, the values entered on previous lines are not visible, but you can see them by pressing the **up arrow** key.

3 How to Use FLUME

3.1 The Main Menu

The FLUME program menu consists of five branches (Figure 3.1):

MAIN MENU F L U M E SYSTEM

SELECT FLUME EDIT FLUME DATA DESIGN FLUME REPORTS/GRAPHS OPTIONS

Figure 3.1 The main branches of the FLUME menu

Except for the initial setup of flume options, the main menu is set up so that you move from left to right. You first select a flume for use, and then either enter actual flume dimensions, or develop a design and finally generate reports (e.g., rating tables, equations) or graphs. The **Select flume** branch was described in Section 2.4. The **Options** branch is used to handle the database (Section 2.3), to set the units in which input and output data will appear, and to set up various computer system parameters (Section 2.2). Chapter 3 deals with the remaining three branches, the main working areas of FLUME, which are described below.

3.2 Edit Flume Data

The **Edit flume data** branch of the main menu is used to enter data on an existing flume or weir, thus one having known dimensions. This menu branch consists of two sub-branches:

EDIT FLUME DATA

General data
Flume dimensions (graphic)

Before the **Edit flume data** branch can be entered, you must have selected a flume in the **Select flume** branch of the main menu (Section 2.4). You do not need to use the **Edit flume data** branch of the menu before entering the **Design flume** branch. You can review the performance of the existing structure, however, by using the **Review design** option under **Make design** (Section 3.8). To enable the review procedure, you must enter the minimum and maximum discharges to be measured and the related tailwater depths (Section 3.5.2).

3.2.1 General Data

When you enter this sub-menu, the following menu block pops up together with the currently selected (or default) information:

Description of flume	Example structure in manual
Type of structure	**Stationary crest**
Construction material	**Concrete smooth** Roughness height: 0.0010000 m

Description of Flume

This option permits you to change the description of the flume in the database. This description will be printed in the heading of the review report, flume data report, and all tables. Hence, a redescription should generally be done if an existing flume is retrieved from the database and subsequently edited to fit the current conditions. The procedure to change the current description is:

1 Hit **enter**. The above window will disappear and be replaced by a double-lined window around the current description.
2 Type new description in available space and hit **enter**.

You will now be back in the above window. If other data have to be changed, use the **arrow** keys to move to that option. Hitting **Esc** returns you to the **Edit flume data** menu.

Type of Structure

Two options are available for the type of structure that can be designed by FLUME: a stationary crest (Figures 1.4 through 1.7), and a movable crest (Figures 1.9 and 5.4). To change the selected type of structure, if need be:

1 Use the **arrow** key to select the **Type of structure** option and hit **enter**. You have now moved to the window:

Stationary crest	Movable crest

2 Use the **arrow** keys to toggle to the desired choice and hit **enter**. You have now returned to the first window with the new type of structure.

Construction Material

To enable the calculation of the energy loss due to friction between the gauging station and the control section, you need to enter a value for the 'absolute roughness height', k, of the construction material of the flume or weir. To edit the description of the construction material and the related *k* value:

1 Use the **arrow** key to select **Construction material** and hit **enter**. The following window will now be shown:

```
Use F1 or F4 for a list of common values
Concrete smooth
Roughness height   :     .0010000 m
```

2 A condensed version of Table 6.1 will appear on-screen to assist you in selecting a value of *k* upon hitting **F1** or **F4**.

3 Use the **arrow** keys to move to the construction material of the structure and hit **enter**. The selected material and related *k* value will now be shown next to the first menu window.

You may select an *k* value other than those shown in the 'help' screen. To enter such a value, the procedure is (hit **Esc** to escape from the 'help' screen)

2a Type name of construction material and hit **enter**. The cursor has now moved to the block with the numerical *k* value.

3a Type the user-selected *k* value and hit **enter**. The selected material and related *k* value will now be shown next to the first menu window.

When values are not entered from the table, you are responsible for ensuring that the word description of the construction material and the numerical values correspond to one another. The structure material description is only included for your information; only the *k* value is used by FLUME.

3.2.2 Flume Dimensions (Graphic)

The **flume dimensions** entry screen has six menu options as shown in the upper right corner of the graphic screen (Figure 3.2).

The procedure used to enter graphic data is:

1 Use the **arrow** keys to select a sub-menu.
2 Press the **enter** key to activate the selected part of the graphics screen.

Data entry for the bottom profile is somewhat different than for the three cross-sections. Upon entering the **Edit bottom profile** option,

3 The **arrow** key only moves the highlighted block between those flume parts that can be altered. (This is just like a sub-menu except that letter keys do not work to select item.)
4 Upon hitting **enter**, the dimensions under this flume part will also be highlighted.
5 Type the new dimensions and hit **enter** again. The graphic screen will be redrawn to the new dimensions.
6 Repeat Steps 3 through 5 for other data to be changed.
7 Hit **Esc** to return to the menu at the upper right corner of the screen.

Data on the upstream ramp slope and the length of the downstream expansion are

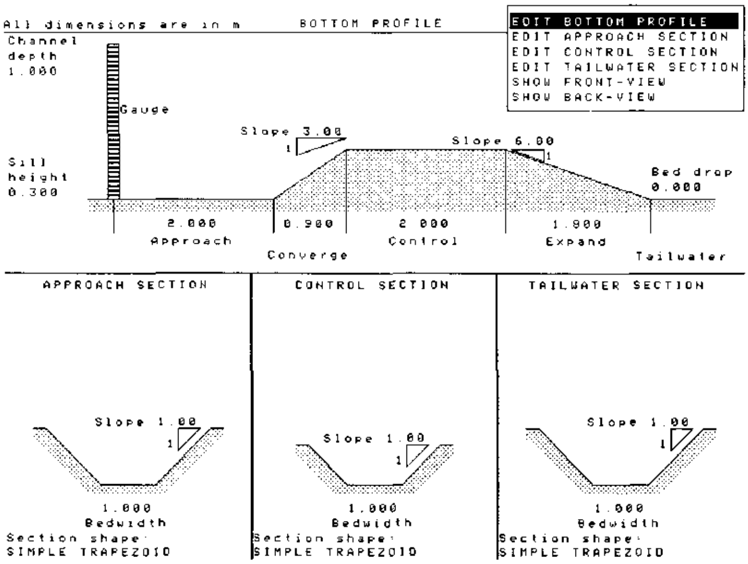

Figure 3.2 Graphics data entry screen for default flume

calculated by FLUME and are shown for information only.

When one of the three **Edit cross section** options is chosen, a new menu is shown which allows you to select the cross-section shape. For the approach section and the tailwater section, select from among the seven shapes of Figure 3.3a. For the control section, fourteen shapes are available (Figure 3.3b). With movable weirs, the shape of the control section is limited to rectangular or a V-shape within a rectangle. If a movable weir is selected, the shape of the control section will default to rectangular under the **Flume dimensions (graphic)** sub-menu.

The procedure to edit data on the cross section at the lower half of the graphic screen is:

8 Move to the shape of the section being considered by using **arrow** keys and hit **enter**. A sub-menu (in graphics form) will pop-up, which allows you to alter the dimensions of the cross section (Figure 3.4).
9 Type the (measured) dimension in the highlighted block and hit **enter**. The next dimension will now be highlighted. If a dimension is already correct, just hit **enter** to move to the next dimension.
10 Repeat Step 9 until all dimensions are correct.
11 Hit **Esc** to return to the main graphic screen when done. This screen will be redrawn to show the entered flume dimensions.

For the cross section screens, data are entered sequentially. You cannot return to a data field already entered without completing data entry for that shape.

In addition, there are two options to show the channel and control cross-sections superimposed on one another. We strongly recommend that you use these options,

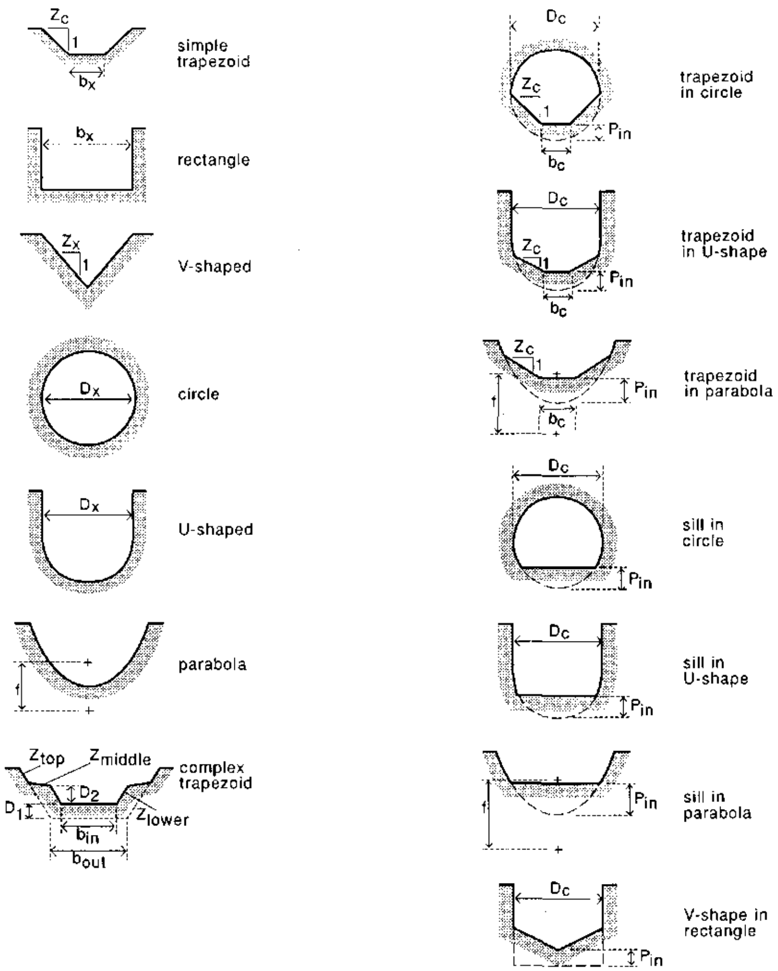

Figure 3.3 Alternative shapes for the approach and the tailwater channels and for the control section

Show front view and **Show back view** after all data have been entered. This allows you to see if the basic data have been entered correctly. As always, **Esc** exits the current menu and moves control to the next higher level menu. You may now move to the **Reports/graphs** branch of the main menu.

FLUME has three other graphic data entry screens which look similar to the **Flume dimensions (graphic)** screen described here, all within the **Design flume** branch of the menu. The first two are used to enter canal data (Section 3.5.1) and initial structure data (Section 3.6.2). Each allows data entry of only part of the displayed data. The final graphics data entry screen is under **Make design** (Section 3.8.3). Under this option, FLUME recomputes the sill bottom width (and inner sill height) when the user alters the profile sill height, according to the design strategy that you have chosen.

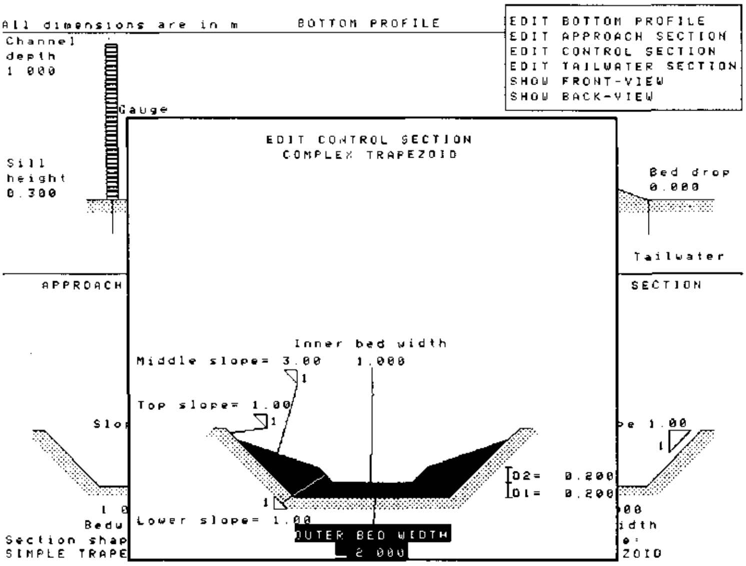

Figure 3.4 Example of a pop-up screen to edit the dimensions of a cross-section (control section)

This allows the user to manually search for design solutions in the same manner as FLUME's design procedures. None of the other screens will alter user-entered values.

3.3 Design Flume

The **Design flume** branch of the program will assist you in designing a long-throated measuring flume or a broad-crested weir. **Design flume** has a horizontal menu consisting of five sub-branches (Figure 3.5). The menu is organized to progress from left to right.

3.4 Site Selection

The sub-branch **Site selection** gives information on factors that have to be taken into account with the selection of a potential site for a flume or weir. Figure 3.5 shows the sub-menu which becomes accessible when you hit the **enter** key. If this is your first time through FLUME, we recommend that you select this **Site selection** menu branch and read the general information on design considerations. It will give you the following information.

3.4.1 Upstream channel

Upstream of the potential site, the channel should be straight and have a reasonably uniform cross-section for a length equal to approximately ten times its average width. If there is a bend closer to the structure, the water surface elevations at the two sides of the channel are different. Reasonably accurate measurements can be made (added

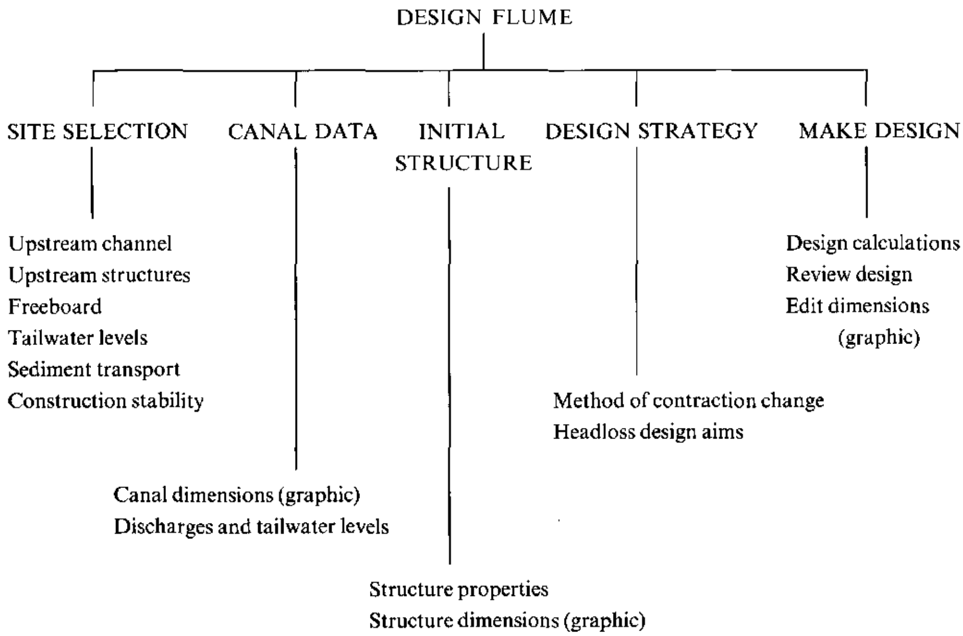

Figure 3.5 The DESIGN FLUME branch menu system

systematic error about 3%) if the upstream straight channel has a length equal to about two times its width. In this case, the water level should be measured at the inner bend of the channel.

To obtain a reasonably smooth water surface whose elevation can be measured accurately, the flow velocity in the approach channel should be limited to that for the maximum anticipated discharge, and the Froude number, Fr_1, should not exceed 0.5 over a distance of at least thirty times h_1 upstream from the structure. If feasible, we recommend reducing the Froude number to 0.2 within the approach section to the flume (see Section 1.3 and Table 5.1 for more details).

3.4.2 Upstream Structures

The weir or flume should be sufficiently far downstream from any structures that discharge highly turbulent water (e.g. undershot gates, drop structures) to enable the accurate measurement of the water level upstream from the planned weir or flume. In practice this means that the flume should be more than twenty times the water surface width at maximum flow downstream from the structure. This distance should be checked in the field.

If no drop in the channel bottom is available to accommodate the head loss required for critical flow in the control section, the flume will cause a rise in the upstream water level. This rise may subsequently reduce the head loss available over the upstream structure. You should check to be sure that it does not lead to an unwanted reduction in the discharge capacity of the upstream structure.

3.4.3 Freeboard

In irrigation canals, the freeboard, F_l, upstream from the flume should be greater than 20% of the upstream sill-referenced head, h_l, at design flow. In terms of constructed canal depth, d_l, this becomes (Figure 3.6);

$$d_l \geq 1.2\,h_l + p_l \qquad (3.1)$$

In natural streams and in drainage canals, a site should be selected which avoids increased innundation at the maximum anticipated flow, Q_{max}. In this context, it should be noted that the head-versus-discharge relationship of the flume is known very accurately (error less than 2%) in comparison with the water-depth-versus-discharge-curve of the channel. Usually, because of uncertainty about the depth-discharge relation, the additional required head falls within the safety margin of the channel freeboard. The program allows the selection of a minimum freeboard at maximum flow.

3.4.4 Tailwater Levels

To obtain a unique relationship between the (measured) sill-referenced head in the approach channel and the (associated) discharge, the upstream water level must be sufficiently higher than the tailwater level (see Sections 4.2 and 6.7). Hence, to enable the design of a structure, the tailwater level, y_2, must be known over the range of discharges to be measured (i.e. minimum and maximum discharge). FLUME offers three methods by which this Q-versus-y_2 curve can be determined (see Section 4.1):

- Linear extrapolation/interpolation through two measured Q-versus-y_2 data points;
- Extrapolation of curve through one measured Q-versus-y_2 point with the use of the Manning equation and the assumption of constant (but unspecified) roughness and slope;
- Calculation of Q-versus-y_2 with the Manning equation and user-given roughness coefficient and slope.

The water level downstream of a planned flume or weir does not always depend on the characteristics of the channel in which the structure is planned or on the discharge to be measured. For example, the tailwater level may be determined by: a downstream structure, flow conditions in a larger channel into which the considered channel dis-

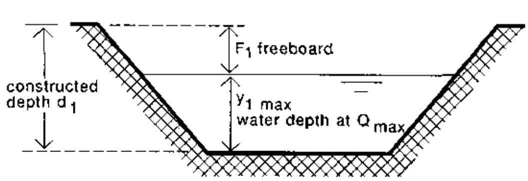

Figure 3.6 Terminology on channel freeboard

charges, or by the operation of a downstream gate. The effects of these conditions on tailwater levels should be known.

3.4.5 Sediment Transport

Besides transporting water, almost all natural streams and drains transport sediment. The most appropriate method of avoiding sediment deposition in the channel reach upstream of the flume or weir is to avoid a decrease in the hydraulic gradient. To achieve this, the structure should be designed in such a way that it does not create a backwater effect with respect to the approach channel bottom. This means that the discharge versus ($h_1 + p_1$) curve of the control must coincide with the discharge versus water depth curve of the upstream channel. This near coincidence should occur for those flows that are expected to transport bed-load material. This design rule requires a drop in the channel bottom at the selected site that is sufficient to guarantee modular flow. Data are needed on (see Section 4.4):
- Shape and dimensions of the upstream channel;
- Available drop in channel bottom at selected site;
- Allowable water depths, y_1, for the considered flow rates.

3.4.6 Construction Stability

In constructing weirs and flumes, the designer may select any locally available construction material (see Figures 1.4 to 1.8). The design should match the permeability and the bearing capacity of the sub-soil. A structure consisting of (wooden) sheet piling and a metal control section can be used if the soil has a very low bearing capacity (Figure 1.10).

To prevent erosion downstream of the weir or flume, the earthen tailwater channel must be protected by riprap over a length which is
- Not less than four times the maximum depth in the tailwater channel;
- Nor less than the earth transition between the structure and the channel;
- Nor less than 1.5 m (5 ft).

Under extreme climatological conditions (frost/heat, wet/dry cycles), extra care must be given to the stability of the structure and the head-detection device with respect to each other. Changes in the relative elevation of these two will cause a systematic head detection error.

3.5 Canal Data

Figure 3.5 shows two menu options under this branch. Here, you enter information about the channel in which the structure is to be placed and on the range of discharges to be measured with the structure.

3.5.1 Canal Dimensions (Graphic)

FLUME can be used to design a flow-measurement or flow-control structure in a channel of arbitrary shape and size. The information required under this menu option include:

- The constructed depth of the channel;
- The amount of drop in the channel bottom;
- Cross-section data for the approach and tailwater sections.

For existing channels, the dimensions of the approach channel and the tailwater channel should be measured in the field. For new channels, they can be read from construction drawings. Canal dimensions are entered in graphical form. (See Section 3.2.2 for details on graphic data entry.)

The graphic screen sections (Figure 3.2) can be edited via a sub-menu shown at the upper right corner of the screen. The options at this location in the menu include:

Edit bottom profile
Edit approach section
Edit tailwater section
Show front view
Show back view

The channel depth and the bed level drop at the site are the only two values that can be entered from the **Edit bottom profile** screen. Because the approach channel and the tailwater channel may have different shapes, dimensions of both channels must be entered separately. You can select from among the seven shapes shown in Figure 3.3a.

These seven shapes pop-up on the graphic screen if you edit either the approach section or the tailwater section (Figure 3.4). Data are entered as described in Section 3.2.2. These seven shapes describe almost all natural and artificial channels.

3.5.2 Discharges and Tailwater Levels

The flow rate in an open channel will vary over time between some minimum and maximum discharge, Q_{min} and Q_{max}, respectively (see Section 4.3). Because the range of flows to be measured with the flume or weir has a major influence on the shape of the control section and on the elevation of the sill with respect to the bottom of the tailwater channel, due attention must be given to this range. Values for Q_{min} and Q_{max} must be entered before design calculations can proceed. If the related screen is entered for the first time, it shows:

Minimum discharge	0.000 m³/s	Tailwater level: 0.000 m
Maximum discharge	0.000 m³/s	Tailwater level: 0.000 m
Determine tailwater levels	Method used: 2 Q-H measurements	

Both discharge values and related tailwater levels show zero values. To enter a discharge value:

1 Select minimum or maximum discharge by using the **arrow** keys.
2 Hit **enter** (Note: the double-lined window will disappear).
3 Type the discharge value.
4 Hit **enter** (Note: the window will appear again).

Because the related tailwater levels have not yet been calculated, the tailwater levels shown will remain zero. If a tailwater level was calculated before, and a new discharge value is entered, the previously calculated tailwater level becomes invalid and will be replaced by zero.

Irrigation canal operation is always such that the ratio Q_{max}/Q_{min} is below 10. In natural streams and drains, however, the range between Q_{min} and Q_{max} is much wider. Hydrological data should be used to determine the relevant values. Section 4.4 gives information on the influence of the ratio Q_{max}/Q_{min} on the suitability of various control section shapes.

The relation between the tailwater depth, y_2, and the discharge, Q, needs to be determined as accurately as practical before a discharge measuring structure can be designed (see Sections 4.2 and 6.7). FLUME actually only uses tailwater depths at Q_{min} and Q_{max}. FLUME offers three methods by which this Q-versus-y_2 relationship can be determined. To select a method:

1 Use the arrow keys to select the **Determine tailwater levels** option.
2 Hit **enter**.

A new menu window will appear on screen showing:

Select method: **2 Q-H measurements** 1 Q-H measurement Manning's equation

3 Use the arrow keys to select one of the methods.
4 Hit **enter**.

Depending on the method selected, a different information and data entry window will appear on screen.

5 Read information and enter data (see details below).
6 Hit **Esc**.

Following data entry, FLUME will use the hydraulic theory of Section 4.1 to calculate y_{2min} and y_{2max} for the range of discharges to be measured (see also Section 3.4.4).

The calculated values will be shown at the upper right side of the screen. You should review the calculated tailwater depth values to ensure that they are reasonable with respect to the channel depth. The calculated values are saved in the database once you direct FLUME to **save flume data**. Intermediate data used to derive these values, which will be discussed below, are not saved in the FLUME database and are only retained while the given flume remains selected. Upon selecting any flume, the selected method always reverts to **2 Q-H Measurements**, since only the calculated depths at Q_{min} and Q_{max} are saved. The options use standard FLUME data-entry procedures

2 Q-H Measurements

With this option, FLUME asks for the entry of measured data on Q-versus-y_2. Two data points must be entered, even if they equal the already entered valves for on Q_{min} and Q_{max}, the discharge value must also be entered. Linear extrapolation/interpolation through these two measured Q-versus-y_2 data points is used to calculate the tailwater levels (see Section 4.2.1).

1 Q-H Measurement

With this second option, you will be asked to enter data for one measured flow rate and the related water depth. Extrapolation of the tailwater curve through one measured Q-versus-y_2 point yields the minimum and maximum tailwater levels. Mannings equation is used, under the assumption of constant (but unspecified) roughness and slope (see Section 4.2.2).

Manning's Equation

Calculation of Q versus y_2 uses the Manning equation. With this third option, FLUME asks for values of the hydraulic gradient, s, and Manning's roughness coefficient, n. A roughness value representing the worst expected seasonal and maintenance conditions of the tailwater channel should be used. To assist with the selection of such a conservative n-value, Table 4.1 will appear on screen if the **F1** or **F4** key is pressed. The procedure to select a value from this table is:

1 Use the **arrow** keys to move to the type of lining of the tailwater channel.
2 Hit **enter**. The selected n-value will be shown to the right of the menu window.

3.6 Initial Structure

This sub-branch of the menu is used to enter data on the general conditions for the structure to be designed, including such things as the type of structure, an initial shape, and allowable errors. The general strategy of the flume design is to start with an initial structure and modify it until the design criteria are met. The menu options provide both the initial **Structure properties** and the **Structure dimensions (graphic)**.

3.6.1 Structure Properties

Upon selection of the **Structure properties** option, FLUME will show the following sub-menu window:

Type of structure	**Stationary crest**
Edit lining type	Lining material: **Concrete smooth** Roughness height: **0.001000 m**
Determine freeboard	**Percentage of head over sill: 20%**
Allowable errors	**8.0%** at minimum discharge **4.0%** at maximum discharge
Head detection method	Head detection method: **Staff in still Fr = 0.2** Precision of reading: **0.0050 m**

All defaulted or previously selected data are printed bold. To change data for each of the entry selections (see Section 2.6 for data-entry procedure):

1 Move cursor to your choice and hit **enter**. The left-hand window will disappear and a new selection window will pop up.
2 Select choices available or type data. Information is given below to assist you in making these choices.
3 Hit **enter**. The menu will return to the left-hand window enabling other data to be changed.
4 Hit the **Esc** key to exit the data-entry window.

Type of Structure

Two options are available on the type of structure that can be designed by FLUME:
- A stationary crest;
- A movable crest.

A structure with a stationary crest is used if the only function of the structure is to measure flow. With these types of weir and flume, all parts of the structure are stationary. Section 1.2 showed some examples of this group of structures. Also the portable RBC flumes fall into this category. The generalized longitudinal profile of stationary-crested structures is shown in Figure 3.7.

If the crest of a weir is made to move up and down, flow over the weir can be regulated and measured at the same time. Weirs with a movable crest can be used at irrigation canal bifurcations (see Figure 5.4) and if water has to be measured in a stream in a flat coastal area where different water levels need to be controlled during the wet and dry seasons (see Figure 1.9). A schematized longitudinal profile over the 'movable' weir is shown in Figure 3.8.

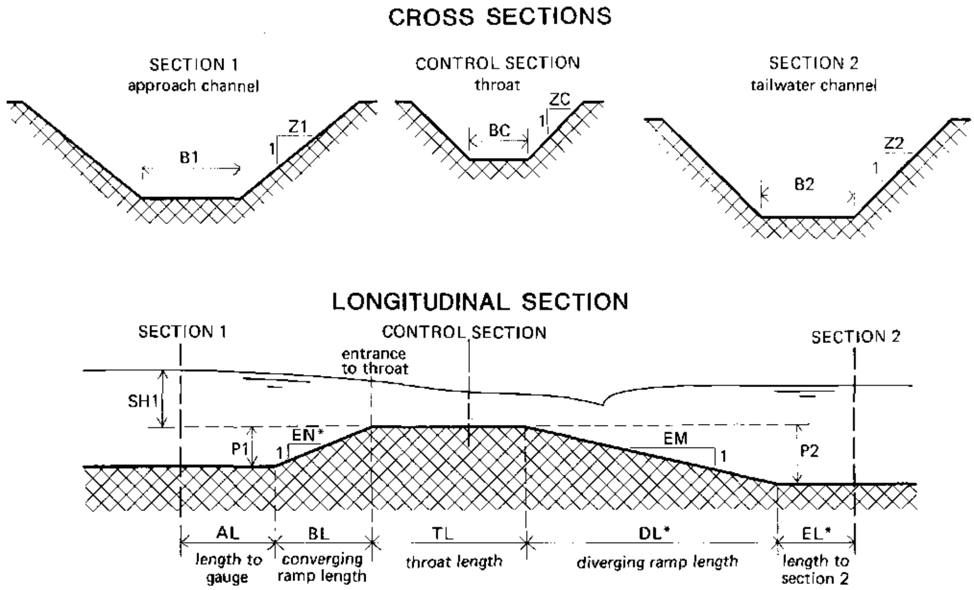

Figure 3.7 Generalized longitudinal profile for a structure with a stationary crest

With movable weirs, the shape of the control section is limited to a rectangle or a V-shape within a rectangle. If a movable structure is selected, the shape of the control section will default to rectangular under the **Structure dimensions (graphic)** sub-menu.

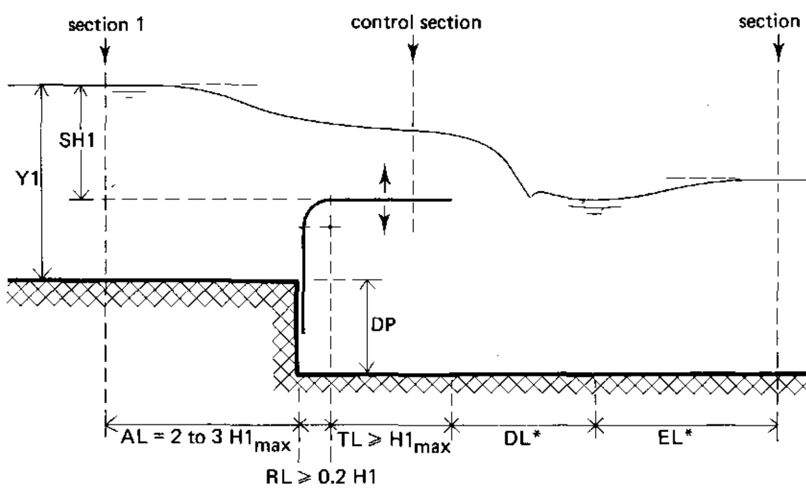

Figure 3.8 Generalized longitudinal profile for a structure with a movable crest

Edit Lining Type

The roughness of the material with which the flume is constructed influences the loss of energy head between the gauging station (where head is measured) and the control section (where the flow rate is controlled). Because the distance between the gauging station and the control section is short, a change in construction material has a minimal, but accountable, effect on the head-versus-discharge rating of the structure. FLUME calculates these friction losses by using the boundary-layer drag theory of Section 6.3. To enable the calculations, you need to enter a value for the 'absolute roughness height', k, of the construction material. By pressing the **F1** or **F4** key, you will make Table 6.1 appear on-screen to assist you in selecting a k-value. The lining material description is only included for your information. When values are not entered from the table, you are responsible for ensuring that the word description of the lining and the numerical values correspond to one another.

Determine Freeboard

To prevent the design of a structure that causes the upstream water level at Q_{max} to be too high, you have to enter a limit on the upstream water depth. This limit may be entered as:

1 A value for freeboard (e.g. in metres).
2 A value for the freeboard, F_1, as a percentage of the sill-referenced head, h_1. A default value of 20% is shown by FLUME (see Equation 3.1). FLUME will determine the sill height, p_1, and head, h_1, in the design branch of the menu, which will then determine the actual freeboard requirement (e.g. in meters or feet).

Allowable Errors

The random error in one single measurement of the flow rate is the result of two contributing sources of errors: (1) the maximum error in the rating table generated by FLUME, X_C, which is about 2%, and (2) the reading or registration error due to the head-detection device used, X_{h1}. Both errors are combined to find the total error in the measured discharge by (see Section 3.9.3 and 4.6)

$$X_Q = \sqrt{X_C^2 + (U X_{h1})^2} \qquad (3.2)$$

The error X_{h1} is given in Table 5.1. As shown, the error is given in length units (mm). At minimum head, h_{1min}, these absolute values may become a significant percentage of h_1. Equation 3.2 shows that this percentage error is subsequently multiplied by the power U of h_1 in the head-discharge equation ($1.5 \leq U \leq 2.5$). Particularly for low heads and a high U-value, care must be given to the head-detection method selected if a small error X_Q in Q_{min} is needed. FLUME uses the default values: $X_{Qmin} = \pm 8\%$ and $X_{Qmax} = \pm 4\%$.

It is important to realize that most errors contributing to X_C and to X_{h1} have a random distribution. Hence, if many (e.g. 15 or more) discharge measurements are made to calculate the volume of water that passes a structure over a period of time (day, week, etc.), these random errors tend to cancel out and can be neglected. As a result, the error in the measured volume of flow is due to systematic errors only. Of these, the errors in zero-setting are the most common (see Section 5.7). Flume construction and calibration errors also result in systematic errors in flow measurements. FLUME will not design a structure with an error of less than $\pm 2\%$ for either Q_{min} or Q_{max}.

Head-Detection Method

The selection of a suitable head-measurement device contributes greatly to the success or failure of the structure and to the accuracy of the measured discharges. The four most important factors that influence the choice of a device are:

- Frequency of discharge measurements: For low frequencies, a dipstick or a staff gauge may be sufficient; otherwise a recorder is needed;
- Accessibility of the measuring site: The cost of taking one head reading is greatly influenced by the time it takes to travel to the site. The cost of a recorder, including its operation, may be less than the accumulated travel cost. This also applies if the site is not accessible during part of the wet or winter season;
- Type of structure over which the head must be measured: In a laboratory, the head over structures is always measured with a point gauge. Portable RBC flumes are commonly used in combination with a dipstick. Weirs with a movable crest are fitted with a device from Section 5.5. Most other structures use either a staff gauge or a (float-operated) recorder.
- Allowable error in the head-detection: As mentioned under **allowable errors**, the permitted error X_{Qmin} determines the error with which h_1 may be measured. As shown in Table 5.1, this error in h_1 is related directly to the selected head-detection device. FLUME will ask you to enter a value for the error in h_1 in length units. By hitting **F1** or **F4** an abbreviated form of Table 5.1 appears to assist in selecting the proper error. The standard data entry occurs as described in Section 2.6.1.

FLUME will use the user-given error in the h_1 measurement to check if the design criteria on the desired percentage error X_{Qmin} can be met. The text describing the head-detection method is for reference only. If you enter numerical values, rather than selecting them from the table, you are responsible for ensuring that the text and numerical values correspond.

3.6.2 Structure Dimensions

The selection of this sub-menu brings you back into the graphics screen. Although this screen looks the same as under the **Canal dimensions** sub-menu (Section 3.5.1), you can now enter structure dimensions only. The sub-menu at the upper right corner of the screen reads:

Edit bottom profile
Edit control section
Show front view
Show back view

Edit Bottom Profile

Under **Edit bottom profile**, you can enter data on the sill height, the length of the approach channel, the length of the converging section, the throat length, and the slope of the downstream expansion. You cannot give the slope of the converging transition or the length of the downstream expansion. They are calculated by the program on the basis of other user-given data. No data on the channel can be entered.

Sill Height, p_1

Under **Design calculations** FLUME will usually increase the contraction in attempting to satisfy the user-given design conditions. For some design options, FLUME cannot design a flume or weir having less contraction than the initial user-given structure. Because the designer does not usually have information on the needed sill height or side contraction, we recommend that you specify minimal or no contraction (p_1 should be less than 15% of the water depth y_1) in the initial structure.

Length of Approach Channel

The gauging- or head-measurement station should be located sufficiently far upstream of the structure to avoid the area of water surface drawdown, yet it should be close enough for the energy loss between the gauging station and the structure to be negligible. This means it will be located at a distance between two and three times H_{1max} from the leading edge of the sill or at H_{1max} from the beginning of the converging transition, whichever is greater (see Section 5.1)

Length of Converging Transition

The function of the converging transition is to provide a smooth acceleration of flow with no discontinuities or flow separation at the beginning of the throat. With stationary structures, the transition commonly consists of plane surfaces. The converging transition should be flatter than 2 to 1 (hor. to vert.). With the movable weir, the transition is usually rounded with a radius equal to $r = 0.2H_{1max}$.

Length of the Control (Throat)

For accurate flow measurement, the throat length, L, is restricted by the value of the sill-referenced energy head, H_1, as:

$$0.070 \leq H_1/L \leq 0.70 \quad 3.3$$

Within this range, FLUME calculates rating tables with an error of less than 2%. Outside this range, this error slowly increases to about 4% at $H_1/L = 1.0$. If a structure is to be designed with a high value of the ratio Q_{max}/Q_{min}, the full range of H_1/L values should be used (see Section 4.3). Under the **Reports/graphs** menu of FLUME, the value of H_1/L can be given as a function of the measured flow rate.

Slope of the Downstream Expansion

If the downstream water level, y_2, is sufficiently low, there is no need for a gradual transition between the throat and the downstream channel. Hence a sudden expansion, zero slope, can be selected. If the head loss over the structure is limited to such an extent that the downstream water head, h_2, becomes higher than the critical water depth in the throat, a gradual transition with a 6-to-1 slope can be added to regain potential energy. The amount of potential energy that can be regained depends mainly on the degree of expansion of the transition. Rather sudden expansion ratios like 1-to-1 or 2-to-1 are not very effective in energy conversion because the high velocity jet leaving the throat cannot suddenly change direction to follow the boundaries of the transition. We therefore advise against using an expansion ratio 1-to-1, 2-to-1, and 3-to-1 (see Sections 4.2 and 6.7).

Edit Control Section

When this option is entered, a sub-menu pops up in the **Control section** part of the screen. Here, you must select the initial shape of the control section. You can choose from among the fourteen listed shapes by using the **arrow** keys. For movable weirs, only two shapes are allowed. If you hit **enter**, the selected shape pops up on the graphic screen. You then enter values for the various dimensions. (See Section 2.6 for data-entry procedures.) It is acceptable, and recommended, to start with no contraction (i.e. a control section that is the same as the approach section).

Show Front View and Back View

You should be sure that the correct values have been entered, giving due attention to the size of the control section relative to the approach channel and the tailwater channel. To allow FLUME to examine a wide range of control sections during design, we suggest that the ratio A^*/A_1 be less than 0.85, where A^* is the area at the control section based on the water surface elevation in the approach channel, and A_1 is the wetted area in the approach channel. To allow the water to decelerate to subcritical flow, the wetted area A_2 of the tailwater channel must be larger than the A^* of the control section after completion of the design.

The options of **Show front view** and **Show back view** can be used to evaluate these sections with respect to each other.

3.7 Design Strategy

The design strategy dictates to FLUME how it should go about determining an acceptable structure. Two groups of criteria are used to describe the design strategy: the **Method of contraction change** and the **Headloss design aims**. As discussed earlier, there may be an infinite number of possible structures which can meet all design criteria. These two sets of criteria are used to guide FLUME towards a solution which is acceptable to the designer. The design criteria are discussed in more detail in Chapter 4.

3.7.1 Method of Contraction Change

This option determines how FLUME will alter the initial control section to arrive at an acceptable design. This is a key option for flume design, and significantly affects the dimensions of the final structure. The four options for altering the initial control section for stationary weirs appear on-screen in a menu block. These options are described below.

SELECT CONTRACTION STRATEGY
Raise height of still
Raise or lower entire section
Raise or lower inner section
Vary side contraction

For movable weirs, the only option of contraction change is: **Vary side contraction.** In none of the four strategies are the side slopes of the control section changed. If you want to change the side slope, you must do it manually. There may be situations where a change in side slope will be needed to find a feasible design.

You may have to try more than one contraction strategy to arrive at an acceptable structure. For example, if you start with no contraction, either 'Raising height of sill' or 'Vary side contraction' may not provide an adequate design, but manually adding a low sill and then selecting 'Vary side contraction' may give an acceptable solution.

Raise Height of Sill

Under this option, the bottom of the control section is moved vertically while all the other parts remain in the same position relative to the approach channel. This, for example, is the option to use for designing a broad-crested weir in a lined canal. In some cases, the shape actually changes with this option. For example, a sill in a U-shape could become a rectangle (bottom moved above circular part of U), or a trapezoid in a circle or in a parabola could become a sill in a circle or parabola respectively.

> FLUME will not lower the sill from the initial shape. We therefore recommend starting with a very low sill or no sill at all!

Raise or Lower Entire Section

Under this option, the entire control section is moved up or down relative to the approach channel bottom to provide the desired amount of contraction. The shape and the dimension within the control section will never change under this option. Hence, the amount of contraction is changed by raising or lowering the sill height, p_1 (p_1 will not be reduced below zero). This option is useful if a standard design (or prefabricated) flume is to be placed in a channel. Such flumes are common for flow-survey work. This option could be used to test the feasibility of using standard-sized structures in an irrigation system.

Raise or Lower Inner Section

This option only applies to the given extra shapes allowed for the control section shapes; a complex trapezoid and either a sill or trapezoid within a circle, a U-shape, or a parabola. The latter three complex shapes are defined in FLUME as a trapezoid with one user-given side slope inside a circle, a U-shape, or a parabola (the second side). The complex trapezoid is defined as a two-sided complex trapezoid within a larger simple trapezoid. In all four shapes, the side of the inner trapezoid must intersect the outer shape.

Under this contraction-change strategy, the inner trapezoid (the part that moves up and down) remains intact, with no changes in dimension values. The outer shape remains fixed, relative to the approach channel, while the inner trapezoid or sill moves up and down. This option is useful for designing a complex flume inside an existing channel, where the existing channel becomes the outer shape, or for designing a trapezoidal control within an existing channel that is circular, U-shaped, or parabolic. This option allows an efficient design without disturbing the existing channel section. FLUME will not reduce the inner sill height below zero.

If the selected shape of the control section is not allowable for this contraction-change strategy, FLUME will choose the strategy '**Raise height of sill**'. In the process, the shape of the control section may change to, for example, a sill within a circle, a U-shape or a parabola.

> To make the outter control section shape coincident with the approach section, the bottom profile sill height and the inner control section sill height need to be identical.

Vary Side Contraction

Under this fourth strategy, the bottom of the control section remains in the same position relative to the approach channel, but the bottom width, b_c, changes to provide the proper amount of contraction. Some shapes do not have a defined bottom width. For those shapes, the diameter (for U-shape and circle) and focus (for parabola) change instead. For the complex trapezoid and the trapezoids inside another shape, the inner bottom width is changed. For a sill inside a circle, U-shape, or parabola, the diameter or focus is changed. For the V-in-rectangle, the width of the rectangle is changed. This strategy is not allowed for V-shaped control sections. It is the only strategy allowed for movable weirs.

> FLUME will not design a structure if the control section is wider than the approach section.

3.7.2 Headloss Design Aims

The options of headloss design aims provide for a fine tuning of the design. In many cases, such fine tuning is essential to the success of the measuring structure. These options only come into play when there is a range of structure dimensions (e.g.

amounts of contraction) over which the design criteria are satisfied. The four options for the headloss design strategy appear on-screen in a menu block. These options are described below.

```
SELECT HEADLOSS DESIGN AIM
Minimize headloss
Maximize headloss
Intermediate headloss
Match drop in canal
```

Minimum Headloss

Under this option, FLUME looks for the amount of contraction that will provide the minimum amount of headloss across the structure, while still meeting all the other critera. The design under this option will cause the least amount of change in the upstream water levels resulting from the installation of the measuring structure.

Maximum Headloss

Under this option, FLUME finds the option that has the highest allowable upstream water level. This option is appropriate when you are very unsure of the tailwater levels and there is plenty of head available across the structure (e.g. a lot of canal slope or a large drop in water surface upstream).

Intermediate Headloss

For this option, FLUME provides an amount of contraction that is midway between the minimum and maximum headloss. This is probably the preferred option in most cases. It allows for some uncertainty in estimates of tailwater levels, but still does not cause unnecessary backwater upstream.

Match Drop in Canal

A natural drop in the channel bottom often makes a good site for a measuring structure since the structure can sometimes be placed so that the water level in the channel upstream is not affected. The idea behind this option is to provide a structure that has the least amount of influence on the upstream water level at maximum discharge. FLUME attempts to match the water depths in the approach and tailwater channels. If this is not possible, FLUME will raise the water level in the approach channel to attain the required headloss. This is the preferred option for channels in which sedimentation is a problem.

It is also possible that you are interested in the flume having a minimum influence on the upstream water depth at minimum discharge as well. FLUME will not do this, so you have to modify the **Initial control section** shape and the **Method of contraction change** to accomplish this through trial designs.

3.8 Make Design

In general, design is meant to be an iterative process. In many cases, FLUME will produce an acceptable design on the first try. In other cases, you will have to spend some time and effort in arriving at a good design. This is partially dictated by the requirements placed on the structure and by the site conditions. The more rigid the demands, the more difficult the design procedure. FLUME is set up to give maximum flexibility for difficult design, while not making the system overly complicated for simple designs. FLUME is NOT an 'expert system' that will make all decisions for you.

There are two common ways to utilize the sub-menu's under **Make design**.

First, the user can execute **Design calculations**, which provides the user with a design results screen. If the design is acceptable, the user may then **Edit dimensions**, for example, to round off design values. Then **Review design** is performed to assure that this editing did not influence flume performance.

Second, the user may want to test the suitability of a proposed structure (e.g. a standard flume type). Then the user would simply select the **Review design** sub-menu.

3.8.1 Design Calculations

The design calculations are performed by FLUME according to the requirements that you have specified under the options **Canal data**, **Initial structure**, and **Design strategy**. FLUME first tests the user-given structure to determine whether the design criteria are met (see Section 3.8.2). If they are not, FLUME attempts to find the amount of contraction required for the maximum allowable water level, as determined by the freeboard requirements, to decide whether a design is feasible at all. An iterative procedure is used to arrive at a control-section shape based on the method of contraction change specified (see Section 6.6.2). If a structure is feasible, the program uses the **Headloss design aims** option to alter the control shape to an appropriate design. FLUME does not round off flume dimensions to even values, but you can do so yourself with the **Edit dimensions** option.

After the **Design calculations**, the program automatically gives a report if a feasible solution is found. Otherwise a message box will appear on-screen as follows:

```
No solution could be found for the set of conditions and dimensions entered
Design procedures failed to arrive at initial solution
Problem  :
Fix      :
Comment :
═══ Exit = Esc ═══
```

Depending on the nature of the problem, the box will show the following information (see also Section 3.8.2):

Stationary Crest:

Contraction Change Strategy: **Raise height of sill**
Problem : Starting with too much contraction in initial shape.
Fix : Start with less (or no) initial contraction.
Comment : The program will not lower an initial sill defined by the user.

Contraction Change Strategy: **Raise or lower entire section**
Problem : Starting with too much contraction in initial shape.
Fix : Start with less (or no) initial contraction.
Comment : The program will not lower bottom of control section below approach channel bed level.

Contraction Change Strategy: **Raise or lower inner section**
Problem : Starting with too much contraction in initial shape.
Fix : Start with less (or no) initial contraction.
Comment : The program will not lower inner sill below invert of outer control section shape (inner sill height of zero).

Contraction Change Strategy: **Vary side contraction**
Problem : Starting with too much contraction in initial shape.
Fix : Start with less (or no) initial contraction.
Comment : The program will not widen control section beyond the width in the approach channel at the maximum upstream water level.

Movable Weirs:

Problem : Starting with an upstream water level that is too low.
Fix : Start with higher upstream water level.
Comment : A small weir radius will reduce the need for higher upstream water level. Also, check upstream Froude number to see if flow is feasible (i.e $Fr_1 \leq 1.0$). We recommend $Fr_1 \leq 0.45$.

If FLUME can design a structure, it will enter into an iteration process (see Section 6.6.2). Upon completion of this process, a design report will be given as follows:

User : Clemmens/Bos/Replogle Report made on: November 20, 1992
Flume: Phoenix, example structure used in manual Version 3

EVALUATION OF FLUME DESIGN

GENERAL RESULT : Design is acceptable. 2 lines of error/warning text.
Headloss design aims are not fully met

EVALUATION OF FLUME DESIGN FOR EACH DESIGN CRITERION

Ok.	Freeboard at Qmax:	Actual = 0.356 m	Minimum = 0.094 m
Ok.	Head at Qmax:	Actual = 0.469 m	Minimum for accuracy = 0.235 m
Ok.	Head at Qmin:	Actual = 0.100 m	Minimum for accuracy = 0.099 m
Ok.	Tailwater depth Qmax:	Actual = 0.844 m	Maximum allowed = 0.858 m
Ok.	Tailwater depth Qmin:	Actual = 0.109 m	Maximum allowed = 0.507 m
Ok.	Froude No. at Qmax:	Actual = 0.315	Maximum = 0.50

ADVICE, WARNINGS, AND ERROR MESSAGES

Headloss design aims are not met.
Too much contraction in initial control section shape

RESULTING STRUCTURE

Sill Height = 0.425 m
CONTROL SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bed width = 1.850 m Channel side slope = 1.00:1

DESIGN STRATEGY

Headloss design aim: Minimize headloss
Contraction change strategy: Vary height of sill

DESIGN CRITERIA

Type of structure: Stationary crest.
Freeboard design criterion: Percentage of head over sill = 20%
Allowable discharge measurement errors for a single measurement:
At minimum discharge: 8.00%. At maximum discharge: 4.00%
Head detection method: Staff in still Fr = 0.2 Readout precision: 0.005000 m
Design discharges and associated tailwater levels:
Minimum discharge = 0.100 m^3/s Minimum tailwater level = 0.109 m
Maximum discharge = 1.300 m^3/s Maximum tailwater level = 0.844 m
Values derived using: 2 Q-H measurements

Use cursor keys, **PgUp**, **PgDn**, etc. to view whole text

A study of the design report may guide you to: select an alternative shape of the control section, change the design strategy, change the allowable error in a single measurement, etc. To enable you to evaluate the effect of such changes, details on the design criteria are given below.

Upon leaving the design result screen report (hit **Esc**), you are given the options:

Output to:	**Screen**	Printer	Disk

- Screen: For showing the report on the screen;
- Printer: For sending the report to a line printer;
- Disk: For sending the report to a disk file. When **disk** is chosen, you are prompted for a DOS file *.TXT to which to send the table. This file will be stored in the FLUME directory.

Freeboard at Maximum Discharge

You may have specified either a minimum (fixed) freeboard height or a minimum amount of freeboard as a percentage of the sill-referenced head, F_{1min} (0.094 m in above example). In either case, this is translated into a maximum allowable upstream water level at maximum flow, y_{1amax}. For the given flume, the actual upstream water level is the sill height, p_1, plus the upstream sill-referenced height at maximum discharge, h_{1max}. The actual freeboard is defined as

$$F_{1actual} = d_l - (h_{1max} + p_1) \qquad (3.4)$$

where d_l is the canal depth of the approach channel. In the design report, $F_{1actual}$ = 0.356 m. The design criterion is

$$\delta F_1 = F_{1actual} - F_{1min} \geq 0 \qquad (3.5)$$

If this criterion is not satisfied, the upstream water level is too high. Thus, the cross-sectional area of the control section is too small at Q_{max}. The possible remedies are to:

- Lower the crest,
- Widen the control section at Q_{max}, or;
- Raise the maximum allowable water level (decrease required freeboard or increase canal depth).

Accuracy at Maximum Discharge

The accuracy of the flow-measuring structure is mainly influenced by the accuracy of head detection of the sill-referenced head in the approach channel, h_1. You have specified the head-detection method (which has a given accuracy of head detection) and a desired overall accuracy. This accuracy includes both the basic accuracy of the structure ($\pm$ 2%) and the accuracy related to head detection. From these, the program can calculate the minimum upstream head required to achieve the desired accuracy at maximum discharge, h_{1amax}. The program calculates the value of h_{1amax} according to the relationships described in Section 6.5 (0.235 m in example). The extra head available above that needed for the given accuracy is

$$\delta h_{1max} = h_{1max} - h_{1amax} \tag{3.6}$$

The design criterion is

$$\delta h_{1max} \geq 0 \tag{3.7}$$

If this criterion is not met, the sill-referenced head is too small at Q_{max}. The possible remedies are to:

- Narrow the control section at Q_{max};
- Use a more accurate head-detection method, or;
- Increase the allowable measurement error at Q_{max}.

Accuracy at Minimum Discharge

Often the accuracy required at minimum discharge is lower than that at maximum discharge because of the smaller relative volume of water involved. If the same accuracies are required at the two discharges, the design criterion at minimum discharge will be more restricting. We suggest using a different required accuracy for these two discharges. In any case, the design criterion at minimum discharge is very similar to Equation 3.6, where

$$\delta h_{1min} = h_{1min} - h_{1amin} \tag{3.8}$$

In the example, $h_{1min} = 0.100$ m and $h_{1amin} = 0.099$ m. The design criterion is

$$\delta h_{1min} \geq 0 \tag{3.9}$$

If this criterion is not met, then the sill-referenced head is too small at Q_{min}. The possible remedies are to:

- Narrow the control section at Q_{min};
- Use a more accurate head-detection method, or;
- Increase the allowable measurement error at Q_{min}.

Modular Flow at Maximum Discharge

When modular flow exists, the upstream water level is not influenced by the water level in the tailwater channel, a necessary condition for accurate flow measurement. Under this condition, the actual tailwater depth at maximum discharge, y_{2max} (0.844 m in example) must be less than the maximum tailwater depth allowed at maximum discharge, y_{2amax} (0.858 m in example), which is calculated by FLUME (Section 6.7). The extra head available at the site at maximum discharge is

$$\delta y_{2max} = y_{2amax} - y_{2max} \tag{3.10}$$

In the example, $y_{2amax} = 0.858$ m and $y_{2max} = 0.844$ m. The design criterion is

$$\delta y_{2max} \geq 0 \tag{3.11}$$

If this criterion is not met, then the upstream water level is too low at Q_{max} (i.e. there is not enough change in water level across the flume). The possible remedies are to:

- Raise the crest;
- Narrow the control section at Q_{max}, or;
- Add a downstream ramp (e.g. change tailwater ramp slope from 0 to 6).

Modular Flow at Minimum Discharge

Modular flow should be maintained throughout the range of discharges to be measured. Except for unusual cases, if the flow is modular at minimum and maximum flow, it will be modular at all flows. This, at least, is the assumption made here. The criterion for modular flow at Q_{min} is the same as for Q_{max} (Equation 3.10):

$$\delta y_{2min} = y_{2amin} - y_{2min} \qquad (3.12)$$

In the example, $y_{2amin} = 0.507$ m and $y_{2min} = 0.109$ m. The design criterion is

$$\delta y_{2min} \geq 0 \qquad (3.13)$$

If this criterion is not met, the upstream water level is too low at Q_{min} (i.e. not enough change in water level across flume). The possible remedies are to:

- Raise the crest;
- Narrow the control section at Q_{min}, or;
- Add a downstream ramp (e.g. change tailwater ramp slope from 0 to 6).

If all these design criteria are met, the design is acceptable. If any of these are negative, the design is not acceptable. There are thirty-two possible combinations of pluses and minuses for these five parameters. Six of these combinations indicate that no design is possible by simply changing the shape of the control section, and one or more of the design limitations must be relaxed (e.g. accuracy, freeboard). In some cases, the program can be requested to move the control section up or down. At the end of the design, the report may suggest that the control be narrowed or widened. Here, you can simply switch the **Method of contraction change** option to **Vary side contraction**. For a more extreme case, the program may suggest widening the control at Q_{min} and narrowing the control at Q_{max}. If so, you should change the shape or the side slopes of the control section.

> There is one combination of conditions not properly addressed by FLUME version 3.0. If the method of contraction change is to raise the bottom sill, and the design is unacceptable because of insufficient accuracy. If the control section is significantly narrower at the bottom than at the top, a feasible design may still be possible. Try increasing the required freeboard to force a lower sill. If one of the modular flow criteria is no longer met, while accuracy is still not met, then no design is possible with the given conditions.

Froude Number at Maximum Discharge

To avoid unpredictable flow conditions in the approach channel (e.g. standing waves), which make accurate flow measurement unreliable, FLUME's design procedures require that the Froude number (Equation 1.1) in the approach channel be less than

0.5. For most channels and flumes, the Froude number increases with an increase in discharge. So, it is only necessary to check the Froude number at maximum flow. If, at the highest upstream water depth (zero freeboard), the approach section Froude number is too high, the approach channel is too small to allow accurate flow measurement with a flume or weir, and FLUME will not be able to find an acceptable design. The only possible way to arrive at an acceptable design is to increase the cross-sectional area of the approach channel. If you have specified some freeboard, you might find an acceptable design by decreasing the specified freeboard.

If FLUME finds an acceptable design, and then tries to reduce the amount of contraction (e.g. to minimize headloss), a high Froude number may result. Here FLUME simply stops trying to reduce the contraction any further and displays the results. The headloss design aims will not have been met if limited by a high Froude number.

Eventually, you should either move toward an acceptable design, or toward a situation that indicates that no design is possible (as discussed earlier in Section 3.8.1). It is up to you, however, whether you want to work on altering the shape, or to simply relax the criteria. FLUME does not do all this automatically. Here, some trade-offs between construction simplicity and expected flume performance (e.g. accuracy of flow measurement) may need to be made. The evaluation of such trade-offs is up to you.

3.8.2. Review Design

The **Review design** option simply indicates whether or not the proposed structure meets the design criteria given in Section 3.8.1 for the given channel conditions. The design report is the same as under **Design calculations**, except that no information on design strategy and results of meeting headloss design aims is displayed. You can enter **Review design** without first doing the **Design calculations**, but then the initial structure should be reasonable. If you alter the flume dimensions with **Edit dimensions**, we recommend that you run the **Review design** option (it is relatively fast). To use the **Review design** option, you must enter values for Q_{min} and Q_{max} under the **Canal data** sub-menu.

After **Review design**, the user has the same options as under **Design calculations** for sending reports to a printer or disk file. An example is shown on page 61.

3.8.3 Edit Dimensions

The **Edit dimensions** option is placed at this location in the menu system to allow you to alter the dimensions (e.g. round them off, or try something new without performing the design calculations) without having to return to the main menu. The procedures used to enter data are described in Section 2.6. We recommend that you return to **Review design** to evaluate the effect of the data editing. The following sub-menus are available for editing data:

Edit bottom profile
Edit approach section
Edit control section
Edit tailwater section
Show front view
Show back view

User :	Clemmens/Bos/Replogle	Report made on: November 20, 1992
Flume:	Phoenix, example structure used in manual	Version 3

EVALUATION OF FLUME DESIGN

GENERAL RESULT : Design is acceptable. 1 lines of error/warning text.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN CRITERION

Ok.	Freeboard at Qmax:	Actual = 0.356 m	Minimum = 0.094 m
Ok.	Head at Qmax:	Actual = 0.469 m	Minimum for accuracy = 0.235 m
Ok.	Head at Qmin:	Actual = 0.100 m	Minimum for accuracy = 0.099 m
Ok.	Tailwater depth Qmax:	Actual = 0.844 m	Maximum allowed = 0.858 m
Ok.	Tailwater depth Qmin:	Actual = 0.109 m	Maximum allowed = 0.507 m
Ok.	Froude No. at Qmax:	Actual = 0.315	Maximum = 0.500

ADVICE WARNING AND ERROR MESSAGES

DESIGN CRITERIA

Type of structure: Stationary crest.
Freeboard design criterion: Percentage of head over sill = 20%
Allowable discharge measurement errors for a single measurement:
At minimum discharge: 8.00%. At maximum discharge: 4.00%
Head detection method: Staff in still Fr = 0.2 Readout precision: 0.005000 m
Design discharges and associated tailwater levels:
Minimum discharge = 0.100 m^3/s Minimum tailwater level = 0.109 m
Maximum discharge = 1.300 m^3/s Maximum tailwater level = 0.844 m
Values derived using: 2 Q-H measurements

Use cursor keys, **PgUp**, **PgDn**, etc. to view whole text

The **Edit dimensions** sub-menu under **Make design** has a special feature which makes it different from the other graphics data-entering screens. Within this screen, the sill height entered from the **Edit bottom profile** screen affects or alters the control section dimensions in the same way as specified by the method of contraction change. For example, if the method of contraction change is **Raise height of sill** and the control section shape is a simple trapezoid, then, if the sill height is changed, the bottom width of the control section will change also. However, you may change the bottom width of the control section without affecting the sill height. This feature is very useful for testing a variety of designs.

Table 3.1 shows the dimensions of the control section shape which are altered by changing the sill height in the **Edit dimensions** screen under **Make design**. The user should become familiar with these options. In any event, a careful review of the final design dimensions should be made. The screens **Show front view** and **Show back view** are useful for a quick look.

Table 3.1 Control section shape dimensions which are altered by changes in sill height within the **Edit dimensions** screen under **Make design**

Contraction change	Simple shapes	Trapezoid within another shape
Raise height of sill	Crest width, b_c	Crest width, b_c, and inner sill height
Raise or lower entire section	None	None
Raise or lower inner section	Not applicable	Inner sill height
Vary bottom width	None	None

3.9 Reports/Graphs

The main functions of the **Reports/Graphs** option are: (1) to calculate data on the head-discharge relation and required head loss from theory, and then to present these results as either a table or a graph, (2) to compare field or laboratory measured data on head versus discharge with parameters as calculated by FLUME, and (3) to produce reports on the (designed) structure. To serve these functions, the following sub-menus are available:

Discharge-head table
Discharge-head graph
Head-discharge table
Head-discharge graph
Measured-data entry
Measured-data table
Measured-data graph
Equation
Wall-gauge data
Flume-data report
Flume-drawing printout

3.9.1 Discharge-Head and Head-Discharge Tables and Graphs

There are two types of rating tables: Head-Discharge and Discharge-Head, which can be saved in the FLUME database. For the Head-Discharge option, you provide a range and increment for head, from which FLUME calculates the discharge. For the Discharge-Head option, you provide a range and increment for discharge, from which the program calculates the related head.

Modify specifications	Calculate/show results

The **Modify specifications** branch of the menu must be entered to specify values on minimum, maximum, and increment values for discharge (or head depending on the option), as shown in the window below.

Present report specifications

Discharge of flume: Minimum = 0.000 m^3/s
Maximum = 0.000 m^3/s
Increment = 0.000 m^3/s

Comment line:

Include extra columns/lines in report:

Froude number	YES	Upstream velocity	NO
Required energy loss	YES	Discharge coefficient	NO
Head/control-section length	YES	Velocity coefficient	NO
Upstream energy head	NO	Max. allowed tailwater level	NO
Upstream water depth	NO	Modular limit	NO

Note: the discharge units shown are as selected under the menu branch **Options**. They can be changed if desired.

The discharge values can also be altered if a value already exists. If no alteration is needed, you can bypass them by using the **down arrow** key. You can select them by hitting the **enter** key (see Section 2.6). After altering these three parameters, use the **down arrow** key to move to a comment line, where you hit the **enter** key if you want to input a comment. This comment will be printed in the heading of the flume design report.

Use the **arrow** key to move down to the report column options. Here you simply indicate which of the parameters you want in the report or graph. Tables are limited to seven columns, two being head and discharge and the other five from the above list. Graphs are limited to four variables plotted against discharge: the upstream head, h_1, plus up to three additional variables from the list. A description of the parameters is given below.

Froude number:	Froude number in the approach channel, Fr_1
Required energy loss:	Headloss between approach and tailwater channels required to maintain modular flow, $H_1 - H_2$
Head/control-section length:	Sill-referenced energy head in the approach channel divided by control-section length, H_1/L
Upstream energy head:	Energy head in the approach channel, H_1
Upstream water depth:	Water depth in the approach channel, y_1
Upstream velocity:	Velocity in the approach channel, v_1
Discharge coefficient:	Ratio of computed over ideal discharge, C_d
Velocity coefficient:	Ratio of discharge based on energy head divided by discharge based on water level (head), C_v

Max. allowed tailwater level:	Maximum allowable tailwater level for maintaining modular flow
Modular limit:	Ratio between downstream and upstream energy heads at the transition between modular and non-modular flow.

To select parameters in the report:

1 Use the **arrow** keys to select the relevant parameter
2 Hit **enter**. A selection box will appear showing:
3 Toggle yes or no and hit **enter** again

TOGGLE
Yes No

After the parameters have been set, you must hit **Esc** to return to the box at the top of the screen. You can now move to the **Calculate/show results** option. The first time through, the program will perform the calculations, displaying the value of head (or discharge) for which the program is calculating discharge (or head). This allows you to observe that the calculations are proceeding. Once the calculations of the rating table are completed, you are given the options:

Output to: **Screen** Printer Disk

- Screen: For showing the table on the screen;
- Printer: For sending the table to a line printer;
- Disk: For sending the table to a disk file. When disk is chosen, you are prompted for a DOS file *.TXT to which to send the table. This file will be stored in the FLUME directory.

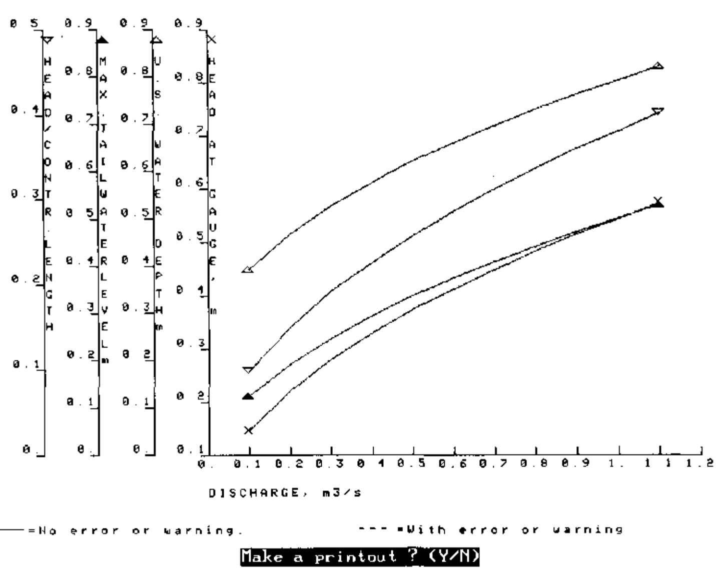

Figure 3.9 Example print of graph showing upstream velocity, upstream water depth, maximum tailwater level, and the sill-referenced head as a function of the discharge

An example of the screen display is printed below

User : Clemmens/Bos/Replogle Report made on: November 23, 1992
Flume : Phoenix, example structure used in manual Version 3
Comment: Other parameters can be selected, if needed

Flow rate m^3/s	Head at gauge m	Froude number	Required head loss m	Upstream depth m	Velocity upstream m/s	Maximum tailwater level m
0.100	0.100	0.064	0.018	0.525	0.125	0.082
0.200	0.155	0.107	0.023	0.580	0.218	0.132
0.300	0.198	0.141	0.026	0.623	0.297	0.172
0.400	0.236	0.169	0.027	0.661	0.365	0.208
0.500	0.269	0.193	0.029	0.694	0.425	0.240
0.600	0.300	0.214	0.030	0.725	0.480	0.269
0.700	0.328	0.233	0.031	0.753	0.530	0.296
0.800	0.355	0.250	0.031	0.780	0.576	0.322
0.900	0.380	0.265	0.032	0.805	0.619	0.346
1.000	0.404	0.279	0.032	0.829	0.660	0.369
1.100	0.426	0.292	0.033	0.851	0.698	0.391

Warnings and error messages:

The table may be longer than displayed and can be viewed by using of the **PgDn** or **down arrow** keys

If a head-discharge (or discharge-head) graph is calculated, the result will be shown on-screen upon completion of the calculations. At the bottom of the screen, the question appears: 'Make a printout ?' Hitting **Y** sends the graph to the printer (see Section 2.2.3 for printer selection). Hitting **N** returns you to the next highest menu level. An example of a graph is shown in Figure 3.9.

You can alter the information displayed by the tables and graphs without re-calculating new values by simply changing the columns to be displayed under modify parameters. FLUME recognizes that only changes in output are requested and does not re-calculate if it is not necessary. If, however, you alter the dimensions of the flume, FLUME will ignore the rating table data in the database with the same name, and re-calculate these tables. Only the last table is saved.

3.9.2 Measured Data Entry Tables and Graphs

To handle and evaluate data on head versus discharge as measured in a hydraulic laboratory or at a prototype structure in an actual channel, FLUME has a special table for data entry. You enter numbers for head and discharge in the table. These values are saved in the FLUME database.

Enter/edit measured values.

Head m	Discharge m^3/s
0.000	0.000

The **arrow** keys are used to move the cursor up and down and from side to side within the table. The **Del** key will delete a record. If you are at the bottom of the table, the **down arrow** key adds a blank record (row) which can be edited to add new data. The **Esc** key is used to leave the data entry table and return you to the sub-menu listing.

Two options are provided to display comparisons between computed and measured results: **Measured data table** and **Measured data graph**. FLUME compares discharges at user-entered values of head. Upon selection of one of these options, you will be back in the **Modify parameters** <——> **Calculate/show result** window. Under the **Modify parameters option**, the following window will appear:

Present report specifications

Comment line:

Include extra columns/lines in report:

Error in discharge	YES		
Discharge error, percent	YES		
Froude number	NO	Upstream velocity	NO
Required energy loss	NO	Discharge coefficient	NO
Head/control-section length	NO	Velocity coefficient	NO
Upstream energy head	NO	Max. allowed tailwater level	NO
Upstream water depth	NO	Modular limit	NO

In addition to the columns, or lines, as described in Section 3.9.1, you can select:

Error in discharge: Difference between discharge value calculated by FLUME and that from your input (measured). This error is expressed in the user-selected units of discharge.

Discharge error, percent: Error in discharge above (discharge calculated by equation minus user-measured discharge) expressed as a percentage of FLUME computed discharge.

Following the same procedure as described in Section 3.9.1 yields a window as shown below:

User : Clemmens/Bos/Replogle Report made on: November 23, 1992
Flume : Phoenix, example structure used in manual Version 3
Comment: Other parameters can be selected, if needed

Head at gauge m	Flow rate m^3/s	Flow rate estimated by model	Error in flow rate m^3/s	Error in flow rate percent
0.100	1.107	0.099	-0.008	-7.700
0.190	0.302	0.280	-0.022	-7.819
0.230	0.390	0.384	-0.006	-1.576
0.261	0.510	0.474	-0.036	-7.554
0.362	0.806	0.827	0.021	2.588
0.422	1.093	1.081	-0.012	-1.139

Warnings and error messages:

If the option **Measured data graph** is selected, the same 'modify parameters' window as above will be available for the selection of three additional parameters per graph. If you hit **Esc** and move to the **Calculate/show result** option, FLUME will recalculate all values. Upon completion, a graph as shown in Figure 3.10 will appear on-screen.

The measured data you entered are saved in the FLUME database. The remaining data in the tables are not saved and are re-calculated each time they are requested.

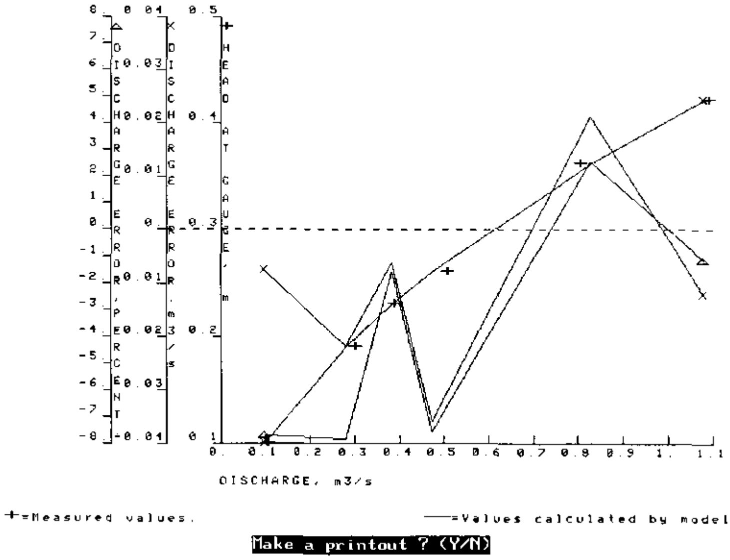

Figure 3.10 Example print of graph showing discharge errors in flow units and in percent, and the sill-referenced head as a function of the discharge

3.9.3 Head-Discharge Equation

Upon selection of the **Equation** option, you will be back in the **Modify parameters** <——> **Calculate/show result** window. Under the **Modify parameters option** the following window will appear:

	Present report specifications	
Sill-referenced head:	Minimum = 0.000 m	
	Maximum = 0.000 m	
	Increment = 0.000 m	
Comment line:		
Equation report format:	**TABLE**	

The **Equation** option uses the head-discharge table from the FLUME database. If data exist from the **Head-discharge** option, FLUME uses those data to determine an equation. The minimum, maximum, and increment values of head that were entered under the **Head-discharge** options will appear in this window. Otherwise head values have to be entered here. These data, however, and the equation data table and graph, are not saved in the FLUME database. They are re-calculated each time. FLUME saves only the last set of heads entered under a **Head-discharge** option.

The equation report is defaulted as a table. An example is shown below.

User : Clemmens/Bos/Replogle Report made on: November 23, 1992
Flume : Phoenix, example structure used in manual Version 3
Comment:

Head at gauge m	Flow rate m^3/s	Equation flow rate m^3/s	Error	Error percent
0.100	0.099	0.100	0.000	0.158
0.200	0.305	0.303	–0.002	–0.665
0.300	0.600	0.601	0.002	0.271
0.400	0.984	0.989	0.005	0.549
0.500	1.459	1.463	0.003	0.231
0.600	2.029	2.018	–0.011	–0.537

Equation: Q = K1 * (H + K2) ** U
Factor values: K1 = 4.843
K2 = 0.019
U = 1.827
Coefficient of determination: 1.000

Warnings and error messages:

The curve-fitting routine used by FLUME is of sufficient quality to generate an equation with a coefficient of determination which approaches 1.000. A minimum of six points (lines in the table) is recommended for curve fitting. The equation always has the form

$$Q = K_1 (h_1 - K_2)^U \qquad (3.14)$$

FLUME also allows you to view a graph showing the head-discharge data points as computed by FLUME versus the head-discharge curve as calculated by the generated equation. For this option, you should return to the **Modify specifications** window. The procedure is:

1 Use the **arrow** key to select the line **Equation report format**.
2 Hit **enter**. This will show:

Equation report format: TOGGLE — **TABLE** Graph

3 Use **arrow** key to toggle and hit **enter**.

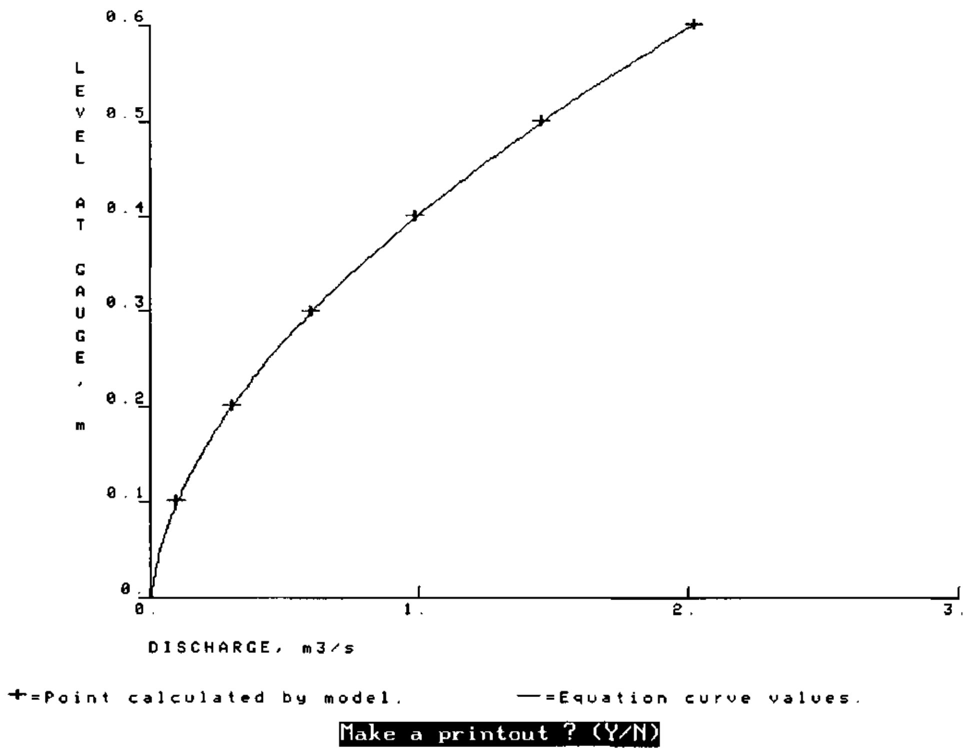

Figure 3.11 Example print of graph showing the head-discharge data points as computed by FLUME versus the head-discharge curve as calculated by the generated equation

4 Hitting **Esc** returns you to the **Modify parameters** <——> **Calculate/show result** window.
5 Moving to **Calculate/show result** and hitting the **enter** key again will yield a report like Figure 3.11.

3.9.4 Wall-Gauge Data

For approach canals with plane-surface, rigid side-walls (e.g. simple trapezoid, rectangle, or triangle made of concrete, brick work, metal, etc.), the wall gauge can be mounted directly on the side slope (Figure 3.12). For sloping canal walls, the length indicated on the gauge will be greater than the corresponding vertical water depth. This option calculates the slope-related distance on the wall gauge with reference to the flume crest or sill. In irrigation canals, it is convenient to mark the gauges of structures in discharge units (m^3/s, *l*/s, cfs, etc.) rather than in head units. Once the gauge has been mounted and checked, this precludes the possibility of using the wrong rating tables. Direct read-out gauges can also be used on movable weirs (Section 5.5).

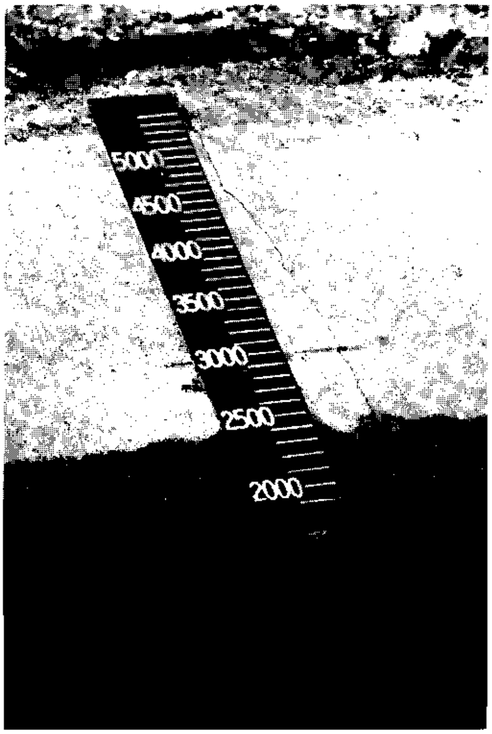

Figure 3.12 An inclined wall-mounted gauge makes a flow-measuring weir more usable. The gauge is marked in discharge units (*l*/s)

Upon entering the **Modify specifications** option of this sub-menu, the following window becomes accessible:

	Current specifications	
Use Q-H rating table	**Yes**	(Discharge interval is constant)
Use H-Q rating table	**No**	(Waterlevel height interval is constant)
Wall gauge slope	**1.0**	:1 (Horizontal/vertical distance)
Reference point	**Crest of sill**	

A constant discharge interval is selected if the gauge is to be marked in discharge units. If constant head units are needed, the *H-Q* rating is set to Yes. The selection can be changed by toggling **Yes** <——> **No** and hitting **enter**. The wall-gauge slope can be changed to the 'as constructed' slope measured in the approach canal. The zero reference level of the length units may be the crest of the sill (default) or the bottom of the approach channel. Moving to **Calculate/show result** and hitting the **enter** key again will yield:

User : Clemmens/Bos/Replogle		Report made on: November 24, 1992
Flume : Phoenix, example structure used in manual		Version 3
Wall-gauge report.	Gauge slope = 1.0 : 1 (horizontal/vertical dist.)	

Wall-gauge data, fixed discharge interval.

Discharge rate m^3/s	Sill-referenced head (vertical) m	Sill-referenced head (along slope) m
0.100	0.100	0.142
0.200	0.155	0.219
0.300	0.198	0.280
0.400	0.236	0.333
0.500	0.269	0.381
0.600	0.300	0.424
0.700	0.328	0.465
0.800	0.355	0.502
0.900	0.380	0.537
1.000	0.404	0.571
1.100	0.426	0.603

The wall-gauge specifications altered in the last menu window, however, and the wall-gauge-data table, are not saved in the FLUME database. They should be re-specified each time. Also the wall-gauge data are re-calculated each time. FLUME saves only the last set of data entered under a **Discharge-head** and a **Head-discharge** option.

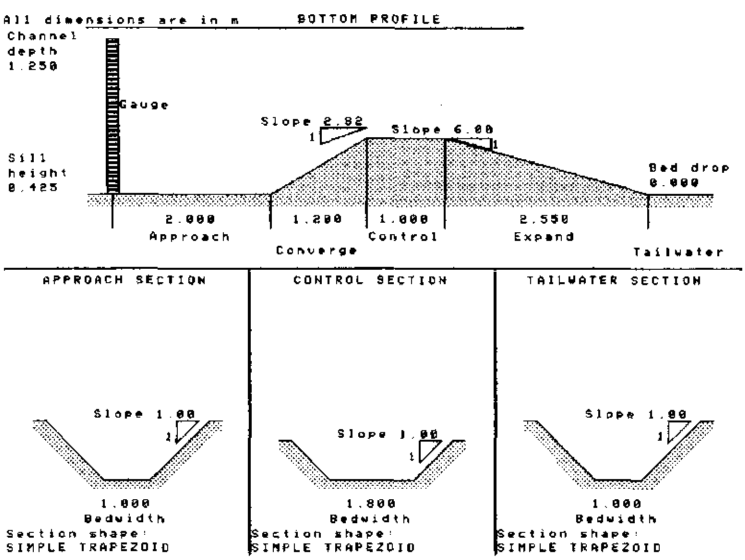

Figure 3.13 Example of FLUME drawing printout

3.9.5 Flume Data Report and Drawing Printout

FLUME allows you to output the dimensions that determine the structure. This includes general flume data and information on the flume bottom profile and cross-sections. An example of a 'flume data report' is given below.

```
User    : Clemmens/Bos/Replogle      Report made on: November 24, 1992
Flume   : Phoenix, example structure used in manual          Version 3
Report on all flume data

                    GENERAL DATA ON FLUME
Type of structure: Stationary crest.
Type of lining: Concrete smooth    Roughness height of flume: 0.00100000 m

                    BOTTOM PROFILE DATA

Length per section:   Approach section = 2.000 m
                      Converging ramp length = 1.200 m
                      Control length = 1.000 m
                      Expansion length = 2.550 m
Vertical dimensions:  Upstream channel depth = 1.250 m
                      Height of sill = 0.425 m
                      Bed level drop = 0.000 m
                      Expansion ramp slope = 6.000:1

                    APPROACH SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bed width = 1.000 m            Channel side slope = 1.00:1

                    CONTROL SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bed width = 1.850 m            Channel side slope = 1.00:1

                    TAILWATER SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bedwidth = 1.000 m             Channel side slope = 1.00:1
==== Use cursor keys, PgUp, PgDn, etc. to view whole text ====
```

Entering the **Flume drawing printout** option returns you to the graphic screen. Instead of the menu option in the top corner, now the question 'Make a printout? (Y/N)' is asked. Hitting **Y** sends a graph as in Figure 3.13 to the printer. Hitting **N** returns you to the menu listing under **Reports/graphs.**

4 Design

This chapter presents some of the issues relevant to the design of flow-measuring flumes: the conditions of the channel in which the measuring structure is placed, and the design requirements which represent the expectations of the designer. The design options and procedures of FLUME were discussed in Sections 3.3 to 3.7.

4.1 Channel Conditions

FLUME can be used to design a flow-measurement or flow-control structure in a channel of arbitrary shape and size provided that an acceptable structure can be placed (Section 1.3). The shapes of the approach and tailwater channels may be different. You can select from among:

Simple trapezoid
Rectangle
V-shape
Circle
U-shape
Parabola
Complex trapezoid

These seven shapes cover almost all natural and artificial channels. The size of the channel cross-section should be read from design drawings or be measured in the field.

4.2 Tailwater Levels

To obtain a unique relationship between the (measured) sill-referenced head in the approach channel and the (to-be-known) discharge, Q, the upstream water level must be sufficiently higher than the tailwater level, y_2 (see Sections 4.3 and 6.7). Hence, to enable the design of a structure, the tailwater level must be known over the range of discharges to be measured. FLUME offers three methods by which this Q-versus-y_2 curve can be determined:

- Linear extrapolation through two measured Q-versus-y_2 data points;
- Extrapolation of curve through one measured Q-versus-y_2 point with the use of the Manning equation and the assumption of constant (but unspecified) roughness and slope;
- Calculation of Q versus y_2 with the use of the Manning equation and the user-given roughness coefficient and slope.

4.2.1 Two Points

In this option FLUME will ask you to provide two sets of data on Q versus y_2. You can obtain these two sets of data points by measuring the discharge at the site where the structure is to be constructed. For new canals, the data points can be taken from the design report. If two points are given, FLUME will generate a Q versus y_2 curve with the shape

$$Q = K y_2^U \tag{4.1}$$

The value of K depends on the size of the channel. The value of the power U depends on the shape of the channel. For wide and shallow channels, U is about 1.6, while for deep and narrow canals, U may be as high as 2.4.

To obtain a reasonably accurate estimate of the tailwater depth at Q_{min} and Q_{max}, the two measured data points should be as near as practical to these minimum and maximum discharges to be measured (Figure 4.1). The program will calculate the tailwater levels at Q_{min} and at Q_{max}.

The water level downstream of a planned flume or weir does not always depend on the characteristics of the channel in which the structure is planned or on the discharge to be measured. For example, the tailwater level may be determined by a downstream structure, flow conditions in a larger channel into which the considered channel discharges, or by the operation of a downstream gate. In these circumstances this 'two points' option must be used to document the Q-versus-y_2 relationship. Under these tailwater conditions, the tailwater level at Q_{min} may have a major influence on the crest level of the weir.

4.2.2 One Point and Manning Equation Extrapolation

The hydraulic calculation of the discharge versus water depth of a channel is based on the continuity equation

$$Q = A\,v \tag{4.2}$$

and on the Manning equation

$$v = \frac{1}{n} R^{2/3} s^{1/2} \tag{4.3}$$

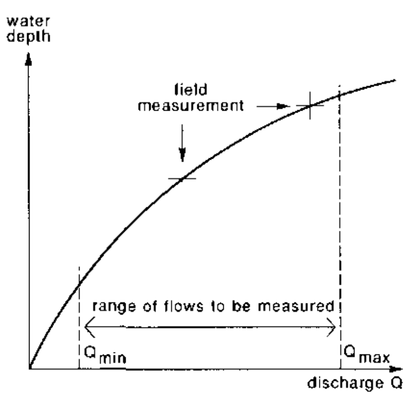

Figure 4.1 Terminology on water level versus discharge curve of a channel

where A is the area of flow, v is the average flow velocity, n is the Manning roughness coefficient, R is the hydraulic radius, and s is the energy gradient. In the program, we assume that the energy gradient equals the canal bed slope. Substitution of Equation 4.2 into 4.3 gives

$$Q = \frac{A}{n} R^{2/3} s^{1/2} \qquad (4.4)$$

If one field measurement of the water level and the discharge is available, the values of Q, A, and R are known. The calculation of the normal canal water depth for flows other than the existing (measured) flow is based on the assumption that the canal bed slope is constant, and that the roughness coefficient is constant with flow stage and time. Neither assumption is strictly true, but the change with stage in the ranges encountered in a given channel is much smaller than the seasonal and maintenance changes that occur. The probable maintenance procedures, biological growths, chemical precipitants, and silt accumulation can all affect the tailwater level. Usually, the worst expected seasonal and maintenance conditions should be selected to describe the tailwater level.

Equation 4.4 can be rearranged to read

$$\frac{s^{1/2}}{n} = \frac{Q}{A\,R^{2/3}} \qquad (4.5)$$

When Equation 4.5 is applied to different discharges while $s^{1/2}/n$ remains constant, we can write

$$\frac{Q_1}{(A\,R^{2/3})_1} = \frac{Q_2}{(A\,R^{2/3})_2} \qquad (4.6)$$

Note that, for this method, values for s and n need not be determined individually. To illustrate how the method can extrapolate the tailwater level, we shall use the example of Figure 4.2.

> **Given:** At the known discharge of 0.150 m^3/s, the water depth $y_2 = 0.43$ m.
> **Question:** What is the water depth at $Q = 0.060\ m^3/s$?

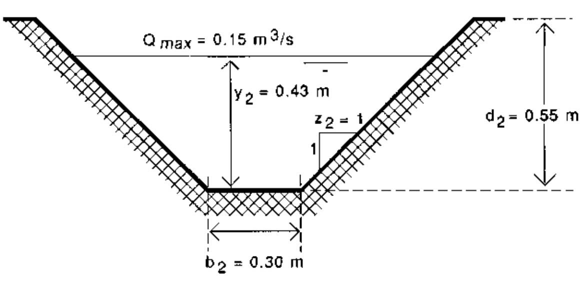

Figure 4.2 Example of the extrapolation of tailwater levels using one set of data points and Manning's equation

For the trapezoidal canal in this example, the area of flow is

$$A_{150} = y_2 (b_2 + z\, y_2) = 0.31\, m^2 \tag{4.7}$$

and the wetted perimeter, P, equals

$$P_{150} = b_2 + 2y_2 \sqrt{1 + z^2} = 1.52m \tag{4.8}$$

Hence, the hydraulic radius at $Q = 0.150\ m^3/s$ is

$$R_{150} = A \,/\, P = 0.21\, m \tag{4.9}$$

For $Q = 0.150\ m^3/s$, substitution of all known values into Equation 4.6 yields

$$\frac{0.15}{0.31 * 0.21^{2/3}} = \frac{0.06}{(A\ R^{2/3})_{60}} \tag{4.10}$$

Thus, if $Q = 0.060\ m^3/s$

$$(A\ R^{2/3})_{60} = 0.40 * 0.31 * 0.35 = 0.043\ m^{8/3} \tag{4.11}$$

Equations 4.7, 4.8, 4.9, and 4.10 represent four equations with four unknowns: y_2, A, P, and R. Outside FLUME, these equations can be solved with a pocket calculator. FLUME uses a trial-and-error procedure to solve for y_2. For this example, with $Q = 0.060\ m^3/s$, the normal water depth is $y_2 = 0.26$ m.

4.2.3 The Manning Equation

If a flume is to be designed in a new canal, the shape and dimensions of the canal should be taken from the design drawings. Also the canal bottom slope should be taken from these designs. With respect to the Manning roughness coefficient, however, a value should be selected that reflects the worst expected seasonal and maintenance conditions. This n-value should thus be higher than the n-value used in the canal design. The n-values given in Table 4.1 can be used for a tentative estimate.

Table 4.1 Conservative values of Manning's roughness coefficient to estimate water levels downstream of a flume

Type of channel and description	Conservative n-value
Concrete-lined	
Float finished	0.018
Float finished, with gravel on bottom	0.020
Gunite	0.025
With algae growth	0.030
Masonry	
Cemented rubble	0.030
Dry rubble, open joints	0.035
Earthen channels	
Straight and uniform, few weeds	0.035
Winding, cobble bottom, clean sides	0.050
Non-uniform, light vegetation on banks	0.060
Not maintained, weeds and brush uncut	0.150

For this option, FLUME will ask you to give an n-value and the *energy* gradient. Subsequently, it will calculate the tailwater levels at Q_{min} and Q_{max}.

4.3 Required Head Loss for Modular Flow

At the measuring site, energy head loss may be available because of a drop in the channel bottom, or you can make it available by allowing the flume to create a rise in the upstream water depth. The first option is often true in natural streams and in newly designed canal systems; the second option often occurs if a structure has to be retrofitted to an existing channel. As illustrated in Figure 4.3, the difference between the upstream sill-referenced energy head, H_1, and the downstream sill-referenced energy head, H_2, can be expressed as $(H_1 - H_2)/H_1$. This ratio can also be written as $1 - H_2/H_1$, the last term of which describes the submergence ratio. For low values of the submergence ratio, H_2/H_1, the tailwater level (and H_2) does not influence the relationship between h_1 and Q, and flow through the structure, or module, is called modular. For high H_2/H_1 ratios, flow in the throat cannot become critical so that the upstream sill-referenced head is influenced by the tailwater level, and flow is then non-modular. That submergence ratio at which modular flow turns into non-modular flow is called the modular limit, *ML* (see also Section 6.7).

If the downstream energy level, H_2, is less than the critical depth, y_c, at the control section, the available head loss exceeds $H_1 - y_c$ and there is no need to transform the kinetic energy at the control section ($v_c^2/2g$) into potential energy downstream of the transition (h_2). In other words, there is no need for a gradual transition between the throat and the downstream channel (Figure 4.4).

If the head loss over the structure is limited to such an extent that the downstream water level, h_2, becomes higher than the y_c-level, a gradual transition can be added to regain potential energy. The amount of potential energy that can be regained

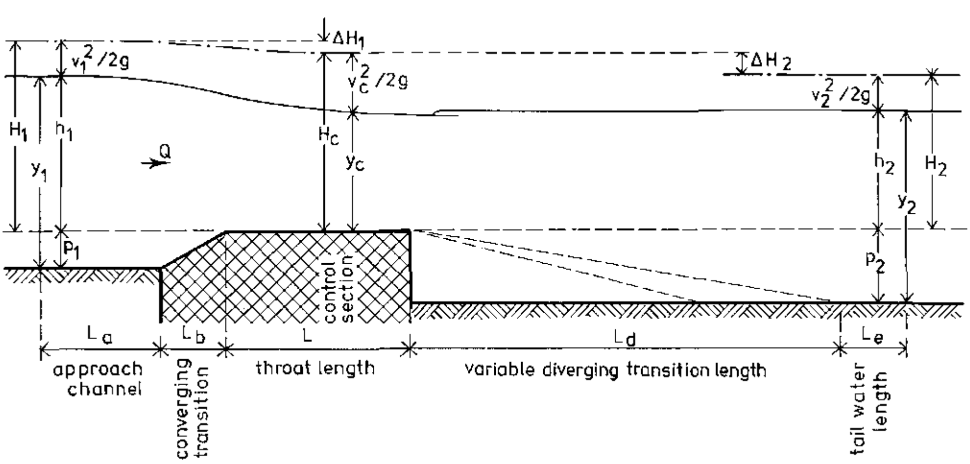

Figure 4.3 Terminology on flow across a flume or weir

Figure 4.4 If the tailwater level is sufficiently low, there is no need for a gradual downstream transition

depends mainly on the degree of expansion of the transition and on the ratio of wetted cross-sectional areas at the control section, A_c, and at the section where h_2 is determined, A_2. The limiting tailwater level, and related H_2-value, to maintain modular flow must thus be determined whenever the available head is less than the H_{max}-values given in Table 4.2.

Table 4.2 Head loss requirement under most unfavourable conditions: sudden transition and $v_2 = 0$ m/s.

Shape of control section	Power U of h_1	y_c/H_1	Minimum modular limit H_2/H_1	ΔH_{max}
Rectangle	1.5	0.67	0.60	$0.40H_1$
Average trapezoid or parabola	2.0	0.75	0.70	$0.30H_1$
Triangle	2.5	0.80	0.76	$0.24H_1$

If the expansion of the downstream transition is gradual (1-to-6), and if the flow velocity in the tailwater channel is high ($v_2 > 1$ m/s), the modular limit of long-throated flumes may exceed $ML = 0.90$ (Figure 4.5). FLUME uses the theory of Section 6.3 and 6.7 to determine the required energy loss over any combination of channel and flume. In the output of FLUME, the following information can be presented as a function of the flow rate:

- Required head loss for modular flow, $h_1 - h_2$;

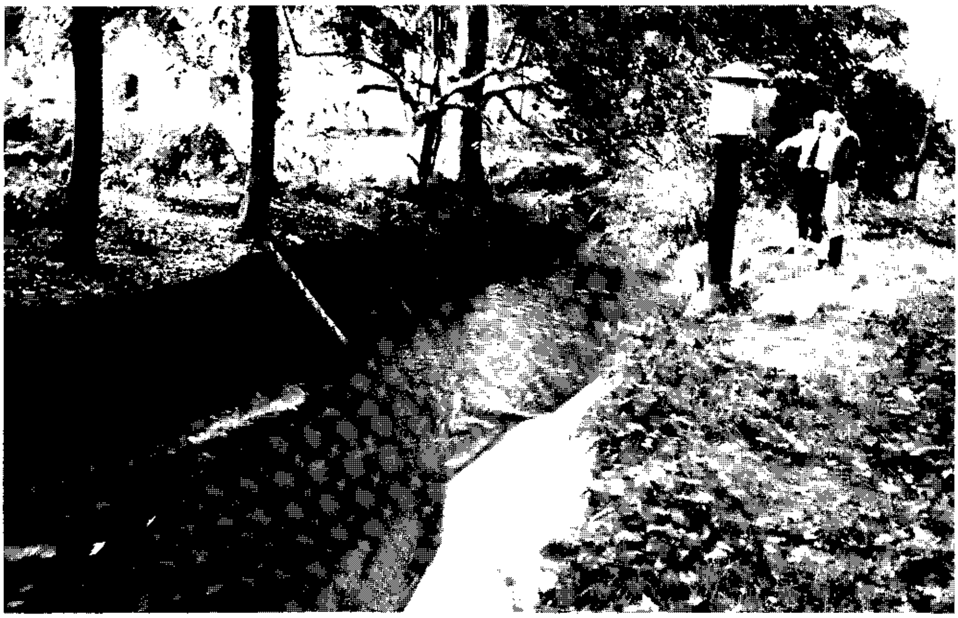

Figure 4.5 Long-throated flume with a modular limit of $ML = 0.90$

- Maximum tailwater depth for modular flow, $y_{2,max} = p_2 + h_{2,max}$;
  Modular limit $ML = H_2/H_1$.

Using FLUME to evaluate the effect of the expansion ratio, EM, will show that the modular limit increases with a more gradual expansion (EM increases). Very gradual transitions ($EM > 10$), however, lose more energy because of friction in the long transition than more rapid but shorter transitions. As a result, the modular limit will not significantly increase. Because the construction cost of a very gradual and long transition is greater than that of a shorter one, we advise that the ratio of expansion be limited to 1-to-6.

Rather sudden expansion ratios like 1-to-1 or 1-to-2 are not very effective in energy conversion because the high velocity jet leaving the throat cannot suddenly change direction to follow the boundaries of the transition. In the flow separation zones that result, eddies are formed that convert kinetic energy into heat and noise. We therefore do not recommend the use of the expansion ratio 1-to-1, 1-to-2, and 1-to-3. If the length downstream of the throat is insufficient to accommodate a fully developed 1-to-6 transition, we recommend truncating the transition to the desired length rather than using a more sudden expansion ratio (Figure 4.6). Truncating the transition to half its full length has a negligible effect on the modular limit. The truncation should not be rounded (Figure 4.6) since this guides the water into the channel bottom, causing additional energy losses and possible erosion.

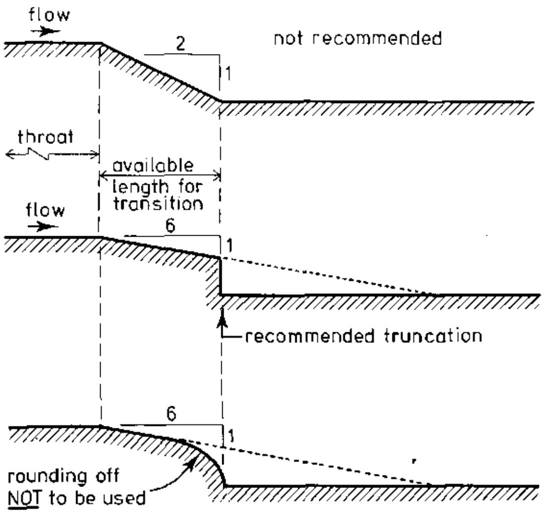

Figure 4.6 Truncation of a gradual downstream transition (Bos, Replogle, and Clemmens 1984)

4.4 Range of Flows to be Measured

The flow rate in an open channel tends to vary with time. The range between Q_{min} and Q_{max} through which the flow should be measured strongly depends on the nature of the channel. Irrigation canals, for example, require a considerably narrower range of flows than do natural streams. The anticipated range of flows to be measured may be classified by the ratio

$$\gamma = Q_{max} / Q_{min} \tag{4.12}$$

For the weirs and flumes described in this manual, the head-versus-discharge relationship can be expressed in the general form

$$Q = C_d K_3 H_1^U \tag{4.13}$$

where C_d is the discharge coefficient which corrects for energy loss due to friction upstream of the control section and for streamline curvature (see Section 6.1), and K_3 is a factor that depends on the size of the structure and on the units in which the discharge is expressed. The power U depends on the shape of the control section as follows (see Section 6.6.1):

$$U = 0.5 + \frac{B_c y_c}{A_c} \tag{4.14}$$

For example, for a rectangular control section, $U = 1.5$, while for a triangular control section, $U = 2.5$. For all other shapes, U ranges between these values.

FLUME calculates a head-discharge rating with an error of less than 2% if the energy head ranges between (see Section 6.3)

$$0.070 \leq \frac{H_1}{L} \leq 0.70 \tag{4.15}$$

Thus, for Q_{min}, the ratio $H_1/L = 0.070$ and C_d averages 0.917; for Q_{max}, the ratio $H_1/L = 0.70$ and C_d averages 1.002 (Bos 1985). It follows that the corresponding range of flows that can be measured by a certain shape of the control section is

$$\frac{Q_{\max}}{Q_{\min}} = \frac{1.002}{0.917} * \left(\frac{0.70}{0.070}\right)^{U} = 1.1 * 10^{U} \tag{4.16}$$

Equation 4.14 shows that the value of U depends on the shape and relative width of the control section. Ranges of U are shown in Table 4.3, together with rounded-off values of Q_{max}/Q_{min}.

Table 4.3 Values of U and Q_{max}/Q_{min} for various control shapes

Shape of the control: Basic form	B_c with respect to h_1 at Q_{max}	U-value	Q_{max}/Q_{min} With rating error $\leq 2\%$	$\leq 4\%$
Rectangular	All	1.5	35	100
Triangular	All	2.5	350	1970
Trapezoidal	Large	1.7	55	180
	Small	2.3	210	1080
Parabolic	All	2.0	105	440
Complex shapes	Large	Variable	>100	>200
	Small	Variable	>250	>2000

In irrigation canals, the ratio Q_{max}/Q_{min} rarely exceeds 35, so that all shapes of the control can be used. In natural drains, however, the range of flows to be measured will usually determine the shape of the control. In natural streams with a small catchment area, the range of discharges to be measured may exceed $Q_{max}/Q_{min} = 350$. Depending on the characteristics of the catchment area, however, neither Q_{min} or Q_{max} contributes much to the discharged volume of water. If a somewhat larger error (up to 4%) can be tolerated in the rating at the extreme flows, the range of flows that can be measured increases considerably to

$$\frac{Q_{\max}}{Q_{\min}} = 1.1 * (1.0/0.05)^{U} = 1.1 * 20^{U} \tag{4.17}$$

The related ranges are shown in the last column of Table 4.3.

4.5 Sediment Transport Capability

Besides transporting water, almost all open channels transport sediments. The most appropriate method of avoiding sediment deposition in the channel reach upstream of the flume or weir is to avoid a decrease in the flow velocity. To achieve this, the structure should be designed in such a way that it does not create a backwater effect. With respect to the approach channel bottom, this means that the Q-versus-$h_1 + p_1$ curve of the control must coincide with the Q-versus-y_1 curve of the upstream channel.

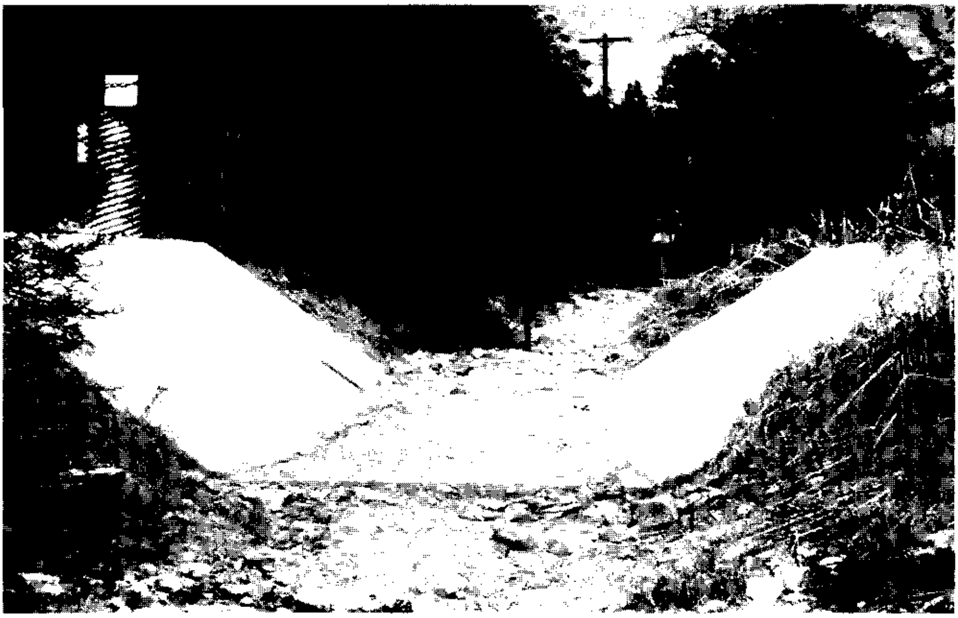

Figure 4.7 Flat-bottommed long-throated flume in sediment-transporting stream. Has been operating since 1970

This near coincidence should occur for those flows that are expected to transport bed-load material.

The above design rule requires a drop in the channel bottom at the selected site; a drop that is sufficient to guarantee modular flow. It also requires that information be collected on the Q-versus-y_l relationship and the dimensions of the channel upstream of the planned structure. Hence, data are needed on:

- Shape and dimensions of the upstream channel;
- Available drop in channel bottom at selected site;
- Allowable water depths y_l for the considered flow rates.

On the basis of these data, FLUME uses the theory of Section 6.6 to calculate the contraction needed for critical flow at the control section. Using the shape you selected for the control section, FLUME uses the theory of Sections 6.3 and 6.7 to calculate the head loss required for modular flow. Following a check against the available head loss, FLUME will give control section dimensions if all demands are met. Otherwise, FLUME will advise a change in design strategy.

Laboratory tests have shown that both long-throated flumes and broad-crested weirs pass all sediment that the upstream channel can transport (Bos 1985). Figure 4.7 shows a flat bottomed long-throated flume that has performed satisfactorily since 1970.

4.6 Required Accuracy of Flow Measurement

4.6.1 Types of Error

Besides the error in the rating table, X_C, the most serious error in the measured flow rate is the error inherent in the determination of h_1. Three types of errors can be distinguished:

Systematic errors
If, for example, the gauge to measure h_1 is installed too low, all 'measured' h_1-values are systematically higher than the true h_1-values until the zero setting of the gauge is checked and the gauge is reset. A systematic error can be corrected if it becomes known.

Random errors
If two people read an h_1-value from a gauge or recorder chart, they will often read different values. A third person again will read another value. Some of the read values are higher and some are lower than the true h_1-value. In other words, the read values have a random distribution around the average true h_1-value.

Spurious errors
These errors invalidate the discharge measurement because of human mistakes or malfunctions in automatic head recorders.

4.6.2 Errors in the Rating Table

The accuracy with which a discharge can be measured with a particular structure is limited by the accuracy with which a measurement can be reproduced. If, independently of each other, two identical structures were to be constructed and flow with exactly the same upstream sill-referenced head, their flow rates would usually not be the same. For the flumes and weirs in this manual, the difference between these flow rates will be less than 2% (error $X_C = 2\%$) if the ratio H_1/L ranges between 0.070 and 0.70 (see Section 6.3.4). Outside this range, the error in the rating table increases to about $X_C = 4\%$ if H_1/L becomes 0.05 or 1.00. FLUME will give a warning if a structure is designed with H_1/L ratios in the range 0.05 to 0.07 and in the range 0.7 to 1.0.

For a given flume, the error in the rating table discharge for a particular upstream head is a systematic error. However, this systematic error is different at different heads, varies with construction anomolies, and is otherwise unpredictable for an individual flow measurement. For this reason, the rating table error is considered here to be a random error.

To justify the use of a rating table generated by FLUME, the constructed dimensions of the structure must be sufficiently close to those given in the related flume drawing or data output. A change in these dimensions will influence the 'error' between the true flow and that indicated by the table. The relative order of magnitude of these added systematic errors is illustrated in Table 4.4.

Table 4.4 Percentage error in the discharge from that indicated in the rating tables due to change in actually constructed dimensions (Bos, Replogle, and Clemmens 1984).

1% change in dimension of:	Resulting percentage error in discharge	Remarks
Upstream ramp length	0.01%	Slope of ramp may vary from 2.5:1 to 4.5:1
Sill height p_l	0.03%	Influences approach velocity
Sill or throat length L	0.10%	Depending on H_l/L value
Bottom width of control section b_c	Up to 1%	Depends on percentage change in wetted flow area at control
Wetted flow area at control section A_c	1%	Linear relationship
1 Degree change of:		
Cross slope of sill	0.1%	Has minor effect on area of flow
Sill slope in direction of flow	Up to 3%	Is most difficult factor to correct for
Side slope of control section z_c	0.5%	Depends on change in wetted flow area A_c

4.6.3 Error in Head Measurements

Errors in upstream head measurement may have a wide variety of sources. Some common sources are grouped below:

Zero Setting

Besides the above-mentioned error in the actual setting procedure of a gauge (see Section 5.7), an unstable foundation for the structure or the head-reading device can cause a drift error in zero setting. If the soil under the structure, stilling well, or staff gauge is subject to ground frost or changes in soil moisture, the zero setting may be altered. To limit the impact of such alterations, it is recommended that the setting be checked at least twice a year when such conditions occur; for example, after a period of heavy frost, after a rainy season, and before the irrigation season. Also, an ice cover on the water may alter the zero setting.

Algal Growth

An important source of a systematic error in head determination is the growth of algae on the bottom and sides of the control. The layer of algae has two effects: (i) the sill-reference level is raised by the thickness of the layer, causing an error in the head, and (ii) the algae layer on the sides of the control reduces the wetted area, A_c. To limit the error due to algal growth (or other dirt), the control must be cleaned with a broom at regular intervals. Painting the structure with a marine antifouling paint will reduce algal growth.

Head-Reading Error

The reading error of a staff gauge is strongly influenced by the distance between the gauge and the observer, the angle under which the gauge must be read, the turbulence of the water, and the graduation unit of the gauge. A dirty gauge face hinders readings and can cause serious reading errors. Staff gauges should therefore be installed in locations where it is possible for the observer to clean them. The approximate magnitude of reading errors on a staff gauge with a 0.01 m graduation is shown in Table 4.5.

Table 4.5 Magnitude of reading errors on a staff gauge

Gauge placed in:	Systematic error	Random error
Standing water	0	0.003 m
Channel with smooth water surface	0.005 m	0.005 m
Channel with turbulent water surface	More than one graduation unit (> 0.01 m)	More than one graduation unit (> 0.01 m)

Table 4.5 shows that, in turbulent water, staff-gauge readings become inaccurate. The systematic error associated with turbulent flow is attributed to the general failure of most observers to average the fluctuating values. Thus, to obtain accurate readings in turbulent water, a stilling well is recommended. The standing watertable inside the stilling well can be measured by a:

Point gauge	to	0.0001 m;
Dipstick	to	0.001 m;
Staff gauge	to	0.003 m;

If the standing water level is measured by a recorder, the error in head registration depends on the float diameter, faulty zero setting, internal friction of the recorder, backlash in the mechanism, etc. The magnitude of most of these errors is inversely proportional to the square of the float diameter. Digital or punched-tape recorders can only register the head with an error of up to half of the registration unit. If a paper chart has to be read, the errors greatly depend on the reduced scale at which it must be read. Depending on the care with which a recorder is installed and maintained, both the systematic and random errors in head will be 0.003 m or more. Errors of over 0.01 m are common for non-maintained recorders. More details are provided in Section 5.6.

Stilling Well Lag Error
Because of the use of a small-diameter connecting pipe in the stilling well design, the water level inside the well will lag behind the outside water level during a quickly rising or falling flow. Such a systematic lag error may also occur if a leaking stilling well is used to measure heads in a lined canal through pervious soils. The water flowing through the pipe to the stilling well requires some head loss; the head in the well will thus be lower than the outside head.

4.6.4 Combination of Errors

As discussed earlier, the measured flow rate is subject to two errors:

- X_C = error in the rating table generated by FLUME;
- X_{hl} = error in the upstream sill-referenced head.

The value of X_{hl} is a combination of all known random errors of h_l calculated by the equation

$$X_{hl} = \frac{100}{h_1}\sqrt{d_{hl}^2 + d_{hu}^2 + \ldots\ldots + d_{hn}^2} \qquad (4.18)$$

where d_{hl}, d_{hu}, etc., are the various random errors in the head measurement. Note that the systematic errors in h_l are then added algebraically to the measured h_l value. The total error X_Q in the measured flow rate can then be calculated by the equation

$$X_Q = \sqrt{X_C^2 + (U\,X_{hl})^2} \qquad (4.19)$$

In the design mode, FLUME asks;

- What is the range of flows to be measured Q_{min} to Q_{max}?
- What is the percentage error that is allowed in **one single** measurement at minimum flow (X_{Qmin}) and at maximum flow (X_{Qmax})?
- What is the random reading error d_{hl} for the selected head-measurement device? See Table 5.1 for common values.

On the basis of the user-selected shape of the control section, FLUME calculates h_{lmin} and h_{lmax} and the value of the power U. Next, it uses Equation 4.19 to check whether the demands of the user on X_Q can be met. Because d_{hl} is an absolute value for a selected head-detection device, the percentage error X_{hlmin} may be too large to meet the user's demands on X_{Qmin}. To solve this problem:

- Select a head-detection method with a smaller reading error so that d_{hl} decreases;
- Select a shape for the control section with a narrower bottom so that h_{lmin} increases;
- Tolerate a larger error in one single measurement of the minimum discharge so that X_{Qmin} increases.

It is important to realize that most errors contributing to X_c and to X_{hl} have a random distribution. Hence, if many (> 15) discharge measurements are made to calculate the volume of water that passes a structure over a period (day, week, etc.) these random errors tend to zero and can be neglected. As a result, the error in the measured volume of flow is due to systematic errors only. Of these, the errors in zero-setting are the most common (see Section 5.7).

4.7 Required Freeboard

Freeboard is designed into channels for several reasons: wave action, changes in channel roughness over time, uncertainty about discharge rates, etc. With reference to Figure 4.8, we can use Equation 4.1 to write

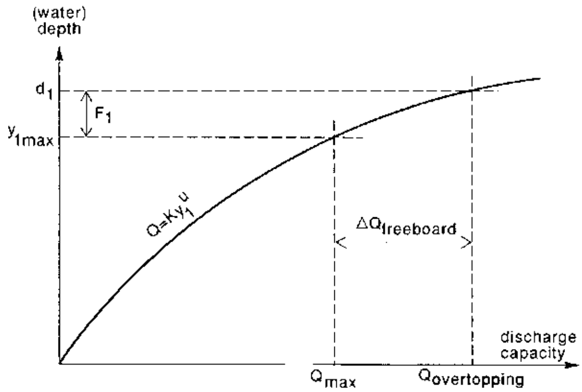

Figure 4.8 Relationship between freeboard and discharge capacity of channel

$$\frac{Q_{overtopping}}{Q_{max}} = \frac{(y_{1max} + F_1)^U}{y_{1max}{}^U} \tag{4.20}$$

If, for example, the freeboard, F_l, of an irrigation canal equals 20% of the water depth at maximum flow, the constructed canal depth is $d_l = y_{lmax} + F_l = 1.2y_{lmax}$. Equation 4.20 then reads

$$\frac{Q_{overtopping}}{Q_{max}} = 1.2^U \tag{4.21}$$

As mentioned in Section 4.2.1, the value of the power U depends on the shape of the channel. For wide and shallow channels, U is about 1.6, while for deep and narrow concrete-lined canals, U may be as high as 2.4. Hence, the extra canal capacity, $Q_{freeboard}$, because of this 20% freeboard, varies between 34 and 55 percent of Q_{max}.

In drainage channels, the design flow rate depends on the selected return period of the discharge from the drained area. The ratio $Q_{overtopping}/Q_{max}$ is determined by the designer on the basis of the function of the channel. If, for example, the ratio is set at 1.50 (50% safety margin), Equation 4.20 becomes

$$1.50 = \frac{(y_{1max} + F_1)^U}{y_{1max}{}^U} \tag{4.22}$$

Since y_{lmax} and the power U of the channel are known, the freeboard F_l can be solved for this safety margin.

When a flume or weir is placed in a channel, the requirements for freeboard upstream of the structure are greatly reduced because the relationship between flow rate and channel water depth is fixed:
- The upstream sill-referenced head is constant for a given discharge;
- Because of the backwater effect of the structure, an increase in channel roughness immediately upstream of the structure has little effect on the water level;
- The future collection of data on channel flow conditions will reduce the uncertainty about the flow rate.

These reductions in possible uncertainty suggest that less freeboard is required in the vicinity of these flumes. For irrigation canals, a freeboard of less than 20% of the maximum anticipated depth is sufficient. Further, we recommend a freeboard amount of less than 20% of the sill-referenced head. In drainage canals, we recommend that a percentage of the design discharge be converted into a freeboard height (see example of Equation 4.22).

5. Measurement of Head

5.1 Introduction

Section 4.6, in discussing the accuracy of one single flow-rate measurement, stated that a knowledge of the true upstream sill-referenced head is necessary for a flow rate to be measured accurately. In fact, the measurement of head is so important that the success or failure of the measuring structure often depends entirely upon the effectiveness of the gauge or recorder used.

The sill-reference level refers to the level of the control section, which is located above the weir crest or in the flume throat at a distance of about $1/3L$ from the downstream edge of the sill (see Figure 5.1). In the direction of flow, the top of the sill (weir crest or invert of flume throat) must be truly level. If minor undulations in level occur, we recommend that the average level at the control section be used as the sill-reference level rather than the average level of the entire sill.

The gauging or head-measurement station should be located sufficiently far upstream of the structure to avoid the area of water surface drawdown, yet it should be close enough for the energy loss between the gauging station and the structure to be negligible. This means it will be located at a distance between two and three times H_{1max} from the leading edge of the sill or at H_{1max} from the beginning of the converging transition, whichever is greater (see Figure 5.1)

The water level at the gauging station can be measured by a vertical or an inclined gauge. A point gauge or a staff gauge is usually suitable when incidental measurements are required, but an automatic recorder is normally needed when continuous records

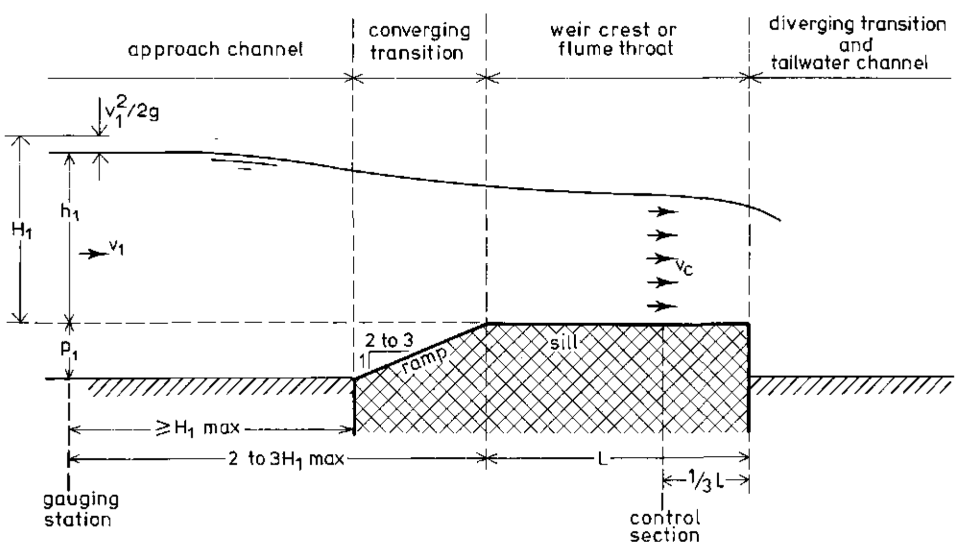

Figure 5.1 General terminology

are desired. Regardless of the type of head-measurement device used, it should be located to one side of the approach channel so that it will not interfere with the flow pattern towards the structure.

5.2 Gauges

When no continuous information on the flow rate is needed, or in channels where the fluctuation of flow is gradual, periodic readings on a calibrated gauge may provide adequate data. Depending on the type of flume and on the required accuracy of the head reading (see Section 4.6), a point gauge, dipstick, or staff gauge may be used.

Point Gauge
A point gauge is the most accurate head-measurement instrument. Its use is normally restricted to research facilities. The point gauge is always used in combination with a stilling well.

Dipstick
The stilling well used in combination with a dipstick should have a sufficiently large diameter so that the stick does not raise the water level upon insertion. Even then, the stick should be inserted slowly until it rests on a reference point whose elevation coincides with the exact sill-reference level. A dipstick can supply very acurate information on head (error of ± 0.001 m). Most portable RBC flumes use a hardwood dipstick which is directly marked in flow rate units (see Figure 1.4).

Staff Gauge
The staff gauge should be placed in such a manner that the water level can be read from the canal bank and so that its surface can be cleaned by the observer. For earthen channels, the gauge can be mounted vertically on a support structure placed in the flowing stream. The support structure should be such that it does not interfere with the flow of water through the flume throat or over the weir crest. Nor should it catch floating debris.

For concrete-lined canals, the gauge can be mounted directly on the canal wall. For sloping canal walls, the length indicated on the gauge will be greater than the corresponding vertical water depth. The relative slope lengths versus vertical lengths for the most commonly used side slopes are given in Figure 5.2 (see also Section 3.9.4).

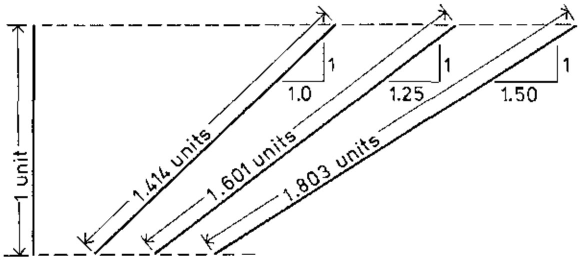

Figure 5.2 Multipliers for units on an inclined gauge

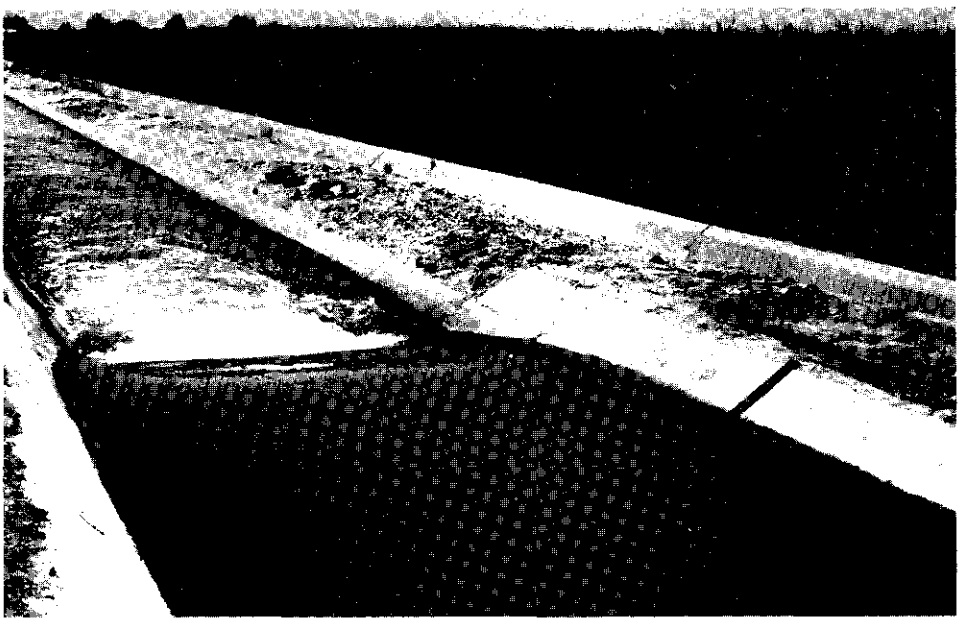

Figure 5.3 The inclined gauge is mounted against the canal side. The gauge shows discharge units

Within an irrigation project, it is convenient to mark the gauges of structures in l/s, m^3/s, ft^3/s, or other convenient unit of discharge rather than in head units. Once the gauge has been mounted and checked, this precludes the possibility of wrong rating tables being used. Direct read-out gauges can also be used on movable weirs (see Section 5.5).

If you ask FLUME to calculate a rating table with discharge versus head units, it will give you the vertical gauge marking distances for a direct reading gauge. Under the **Wall gauge data** option under **Reports/graphs**, you can obtain the dimensions for a gauge mounted directly against the slope of the approach channel. An example of an inclined direct-reading gauge is shown in Figure 5.3. For this gauge, the marks need not be more than about 3 or 4 cm apart, since interpolation between marks will give reasonable accuracy. For example, on the gauge shown, there is a 2.5 cm difference in elevation (4.5 cm along wall gauge) between 2.20 and 2.40 m^3/s. Interpolation between these marks by eye is relatively easy. With experience, an observer can easily read the discharge to within $\pm 4\%$ of the true discharge.

Most permanent gauges are plates of enamelled steel, cast aluminum, or polyester. Baked enamel steel gauges with linear scales are available from commercial sources. These gauges will last for a very long time. Gauges marked in discharge units can be custom-ordered in large quantities, but are considerably more expensive. Spray enamel paints with UV protection can also be used to make gauges on steel. These are not as durable as the baked enamel, but are considerably less expensive. Gauges in discharge units can also be made by stamping aluminum bar stock with a hammer, chisel, or metal-stamping dies. Gauges require periodic cleaning, so they must be accessible.

5.3 Recorders

Automatic water-level recorders are instruments that produce graphic, magnetic tape, or electronic records of water surface elevations in relation to time. Such recorders have the following advantages over ordinary gauges:

- In channels with daily fluctuations of flow, continuous records provide the most accurate means of determining the daily average and total flow;
- The entire hydrograph is recorded with the maximum and minimum water levels as a function of time. This provides data on the reaction time of the channel system to upstream changes in the inflow;
- Observations can be made at remote places where observers are not available or in locations that are not accessible under all weather conditions.

Various meteorological instrument manufacturers produce a variety of commercially available recorders. In this manual, we will not give details of recorders because the descriptions and instructions by their manufacturers are both detailed and complete. Besides, technical progress soon makes any description obsolete.

5.4 Flow Totalizers

Often, the main objective of flow-rate measurement is to obtain information on the volume of water that passes through a channel in a particular period. Calculating this total flow from the recorded hydrograph is a time-consuming job, which is often delayed. To avoid this, commercially available flow totalizers can be used, which consist of the following three components:

- A recording device for the upstream water level;
- A microprocessor which corrects the registered water level to sill-referenced head and calculates the flow rate from the exponential Q-versus-h_l equation for the particular structure;
- A totalizer which instructs the microprocessor to calculate the Q at a pre-set time interval, multiplies the calculated Q by the elapsed time since the previous measurement, and adds this total flow to the grand total.

For this purpose, FLUME generates an equation with the general form

$$Q = K1\,(h_l + K2)^U \qquad (5.1)$$

The units of the factor $K2$ are the same as the head, h_l, the power U is dimensionless, and the units for $K1$ vary with the head and discharge units and the value of U.

To calculate the volume of water that discharges through a flume per day, month, year, etc., many single measurements of head are needed. The error in each single measurement consists of both random and systematic errors. Because the percentage random error in the cumulative flow over the considered period tends to zero and can be neglected, the error in the measured flow volume will be significantly smaller than the error in one single measurement. The error in the measured flow volume will be due to the systematic errors in the rating table (less than 2%), in the head detection (zero setting, recorder), and in the measured dimensions of the flume (Bos 1976).

5.5 Head Measurement over Movable Crest

To control flow over a weir, a crest that moves up and down can be used. Hence, a wall-mounted staff gauge at the head-measurement station does not provide a value for the upstream sill-referenced head, h_1, unless the weir crest elevation is registered separately in terms of gauged head. This can be done automatically with commercially available differential head recorders. Very often, however, a recorder is not needed at each structure. Direct readings of the sill-referenced head, h_1, or of the flow rate can be made with the following scale arrangements, the use of which is strongly recommended in addition to the differential head recorder. Direct reading gauges facilitate weir operation.

Gauge and Scales

Figure 5.4 shows a flow-registration system that is very sturdy and is difficult to alter by unauthorized use. The system consists of two scales and a staff gauge. The first scale, which has a centimetre (or inch) division, is mounted to the stationary guide frame of the weir. The second scale, marked in litres per second (or ft^3/s), is attached by means of a steel support to the hoist strip and lifting beam of the crest. Hence, the first scale has a fixed position while the second scale moves up and down with the weir crest. The numbering on the centimetre (inch) scale is the same as that of the staff gauge installed in the approach channel to the weir.

The litre scale and the centimetre scale are fastened with respect to each other in such a way that if the crest is placed exactly at the approach-channel water level, the reading on the centimetre scale across from the zero on the litre scale is the same as the reading on the upstream staff gauge. If the weir crest is lowered, the weir flow is read across from that point which corresponds with the staff-gauge reading. The procedure to determine the weir flow is:

Figure 5.4 Flow-registration system for a movable broad-crested weir

- Read the gauge in the approach channel and remember this reading;
- Find the corresponding point on the centimetre scale;
- Read the flow rate on the litres/second scale across from this point on the centimetre scale.

Automatic Recorder

Figure 5.5 shows a schematic of a differential head meter that can drive an automatic recorder. The system is designed in such a way that, with either a lowering of the float or a raising of the extended lifting beam, the free-hanging disc wheel C will be pulled down half this distance. Thus a point on the circumference of disc wheel A will move this same 'half distance' against the recorder wheel. Upon adjustment for this 'half' movement of the disc wheel (e.g. with a pulley of different diameter), the difference between the stilling-well water level and the weir crest, being h_l, can be recorded directly.

Zero setting of the recorder can be done by adjusting the swivel or set screw with which the wire is fastened to the extended lifting beam.

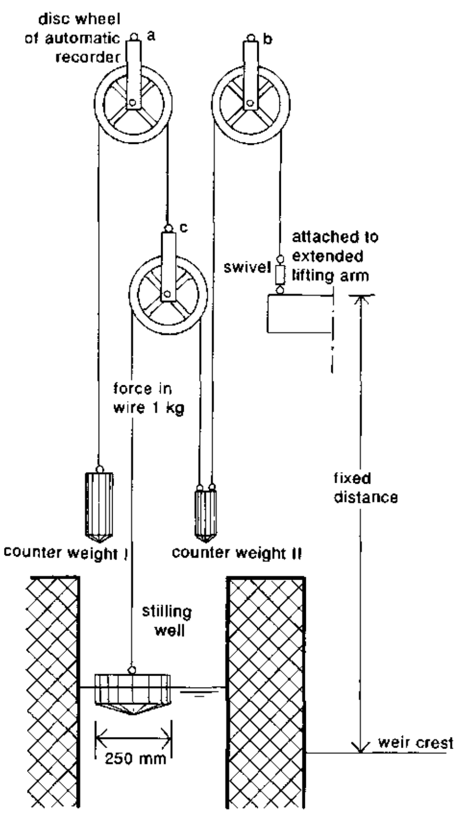

Figure 5.5 Schematic of a differential head meter that can drive an automatic recorder

5.6 Selection of Head-Measurement Device

The selection of a suitable head-measurement device contributes greatly to the success or failure of the structure and to the value of the collected data. The three most important factors that influence the choice of a device are:
- Frequency of discharge measurements;
- Type of structure over which the head must be measured;
- Allowable error in the head detection.

With respect to the first two items, detailed information is given in Sections 5.2 through 5.5. For the third item, we rewrite Equation 4.19 to read

$$X_{hl} = \sqrt{\frac{X_Q^2 - X_C^2}{U^2}} \tag{5.2}$$

FLUME uses a value of $X_c = 2\%$ and calculates the power U from the shape of the control section (see Table 4.3 for U-values). The error X_Q in one single flow measurement is a user-given value for both Q_{min} and Q_{max}. The calculated X_{hl} value is used to calculate the allowable error in h_l

$$\Delta h_l = \frac{h_l \times X_{hl}}{100} \tag{5.3}$$

Common reading errors in sill-referenced head for various devices are listed in Table 5.1. Because of the small value of h_{lmin} at the minimum flow to be measured, the user-

Table 5.1 Common reading errors in sill-referenced head.

Device	Reading error d_{hl} in h_l if head detection is in: Open channel	Stilling well	Remarks
Point gauge	Not applicable	0.1 mm	Commonly used for research
Dipstick	Not applicable	1 mm	Good for research and field use
Staff gauge	4 mm 7 mm >15 mm	4 mm 5 mm 7 mm	$Fr_l < 0.1$ $Fr_l = 0.2$ $Fr_l = 0.5$
Pressure bulb & recorder	Up to 20 mm	Not required	Very suitable for temporary installations (Error is 2% of h_{1max})
Bubble gauge & recorder	10 mm	Not required	Stilling well is not required but can be used
Float-operated recorder	Not applicable	5 mm	Stilling well is required
Flow totalizer	–	–	Some additional random and systematic errors are possible

given error, X_{Qmin}, may be too small to yield a sufficiently accurate head-measuring device from Table 5.1. In this case, you have two choices:

- Allow a greater error in the measured discharge for h_{1min};
- Redesign the structure with a narrower bottom width resulting in a higher value of h_{1min}.

5.7 Gauge Placement and Zero Setting

The accurate determination of the sill-referenced head, h_1, is the most important factor in obtaining accurate discharge measurements. The upstream sill-referenced head, h_1, can be measured by a gauge or recorder only if the observed water level is known with respect to the weir-sill (or flume-crest) level at the control section (see Figure 5.1). The method by which the relative setting of gauge, float, etc., is determined depends on factors such as the canal size in which the structure is located, the flow rate in the channel during the setting procedure, available equipment, etc.

5.7.1 Zero Setting of Recorder

There are several methods for zeroing a water-level recorder, three of which are particularly suitable. The recorder can be set when the canal is dry, when water is ponded over the flume, or when water is flowing through the canal. For all methods, the reference point for determining the upstream depth should be located along the flume centreline at a point roughly $^1/_3$ of the throat length upstream from the downstream end of the throat (see Figure 5.1). This will help to correct for any errors in levelling the flume crest. If the flume is truly level, any point on the flume crest will work adequately. The 'levelness' of the flume crest should be checked during the zero-setting procedure.

The following zero-setting methods assume that the sill-reference elevation can be measured during the procedure. Especially on wide structures, this is not always practical. A stable bench mark (bronze cap poured in concrete) should be added to such structures, the elevation of which is known with respect to the sill-reference point. The second setting procedure can then be used with the point gauge above the bench mark, provided that the stilling-well pipe can be plugged temporarily.

Setting of Recorder using a Pond

In small channels that do not discharge water during the setting procedure, a small pond can be used to set the recorder. Instructions for setting the water level recorder in an existing stilling well are:

1 Form a temporary earthen dam, or place a watertight check gate immediately upstream of the stilling-well pipe and a second dam or gate downstream of the control section.
2 Raise the water level in the thus-formed pond until it is at least 0.05 m above the sill crest, but preferably to the most common (or design) water level in the channel.
3 Place water-level recorder on floor of shelter or on shelf; install all recorder-related equipment in position to record.

4 Observe the record for about 5 minutes to see if the setup is watertight. If the water level drops during this period, find the leak and repair it.
5 Place a dipstick or ruler into the pond at the sill-reference location and read the head over the structure crest/sill to ± 1 mm (0.003 ft). Repeat this step for a check.
6 Adjust the float tape and the tape index pointer in such a way that the above sill-referenced head is read opposite the pointer. (Note: some recorders do not use this setup.)
7 Adjust recorder to show the last reading of the sill-referenced head.
8 Repeat the preceding 7 steps with water at a different level.

Setting of Recorder for an Empty Canal

If the construction of two temporary dams is not practical, the equipment illustrated in Figure 5.6 can be used. The procedure is as follows:

1 Place water-level recorder on floor of shelter or on shelf; install all additional parts in position to record.
2 Install a point gauge in the control section at the centreline of the weir/flume (sill-reference location). Use a temporary, stiff support. Close the stilling-well pipe with a rubber stopper that is penetrated by a pipe to which a transparent hose is connected. The other end of the hose is connected to a small funnel or cup.
3 With the point gauge, take a reading of the weir (sill) or flume throat bottom in the control section. Read to ± 1 mm (0.003 foot) or more precisely.
4 Raise the point gauge sufficiently high so that the funnel can be placed below the

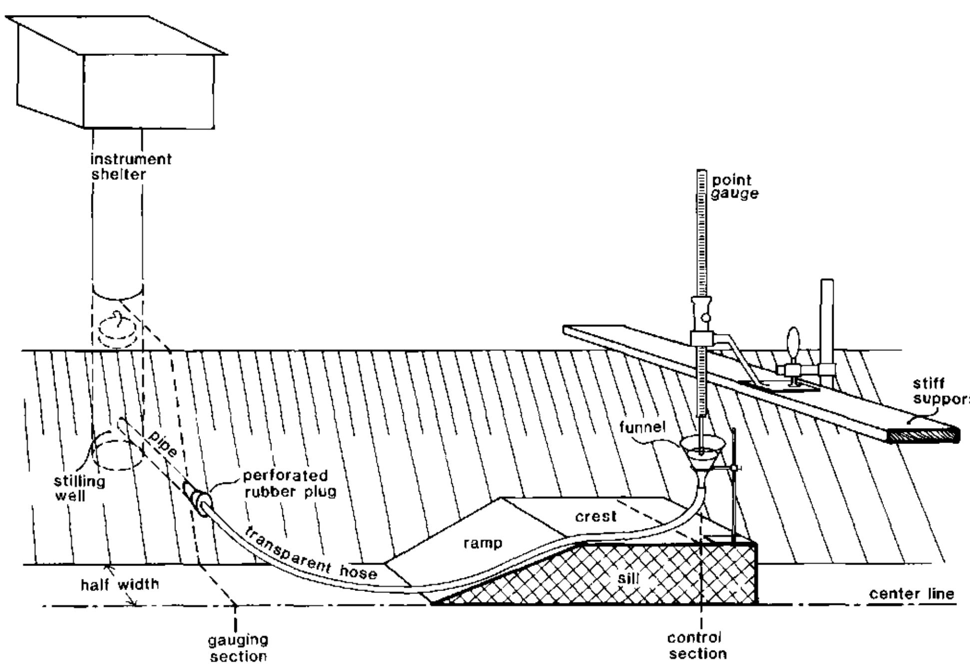

Figure 5.6 Half-view of weir showing zero-setting equipment for an empty canal

point. The funnel support may be either placed on the structure or fixed to the point-gauge support (see Figure 5.6)

5 Add water to the stilling well to raise the water level in the stilling well until it is about 0.01 m (0.03 foot) below the edge of the funnel. Check to see that no air bubbles remain in the transparent hose.
6 Lower point gauge and read water surface in funnel. Read on recorder immediately. Repeat this step as a check.
7 Calculate difference in point-gauge readings to find the sill-referenced head over the structure crest.
8 Set recorder to read sill-referenced head obtained from the difference between the two point-gauge readings.
9 Check the preceding four steps at a different water level to reduce the chance of calculation or procedural mistakes.

Setting Recorder in Flowing Water

This method differs only slightly from the point-gauge method, and can be as quick and reliable as any of the other methods. The apparatus required is shown in Figure 5.7. The procedure is as follows:

1 Place the water-level recorder on floor of shelter or on shelf and install related equipment in position to record.
2 Attach point gauge and funnel or flat-bottomed cup to a rigid support that can span the flow of water. Attach a transparent hose to the perforated sensing pipe.

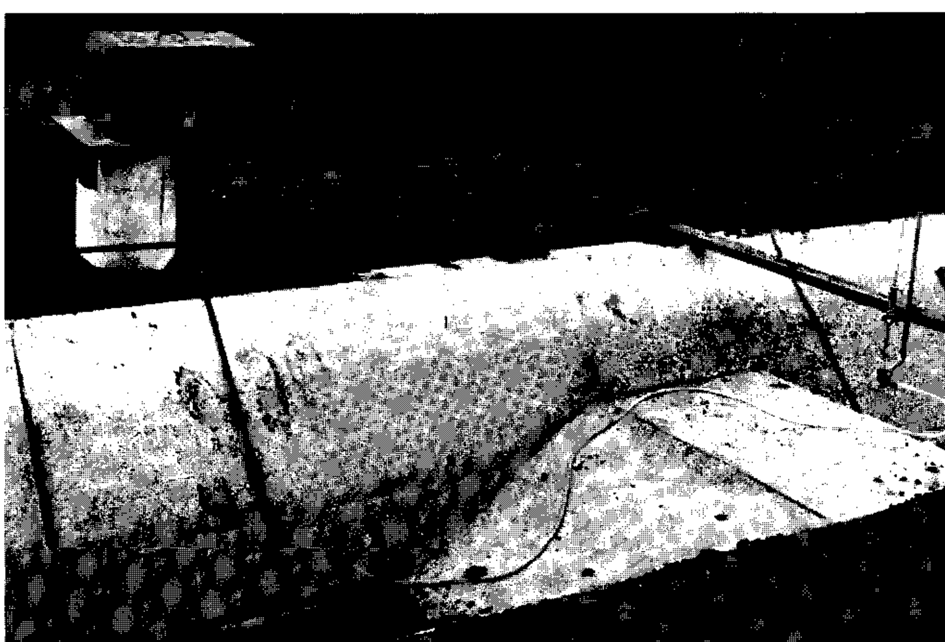

Figure 5.7 Equipment for setting a recorder in a canal with flowing water; this equipment is also used with temporary weirs

The perforations are about 0.3 m from the rounded and closed nose of the sensing pipe.

3 Place support with point gauge across canal. Place sensing pipe in flowing stream, pointing rounded nose directly into the direction of the flow and locating the pipe sidewall sensing holes at the gauging station.

4 With the point gauge, take a reading of the weir (sill) or flume throat in the control section (sill-reference point). Read to $\pm$ 1 mm (0.003 foot) or more precisely.

5 Raise the point gauge sufficiently high so that the funnel or cup can be placed below the point-gauge. (Note: Do not move point-gauge setup in between those readings.)

6 Lower the cup to below water level. Purge air from transparent hose and attach to cup. Raise the cup so that the water level is several centimetres deep in the bottom of the cup, so that the cup is above the flowing water level.

7 Lower point-gauge and read water level in cup. Repeat this step as a check. It may take a minute or so for the water level in the cup to stabilize. Subtract point-gauge readings to determine upstream sill-referenced head to be set on the recorder.

8 Set recorder to read the above head obtained from the difference between the two point-gauge readings. If practical, repeat when water flow has changed somewhat, to verify.

5.7.2 Placement of Staff Gauges

For unlined canals, a vertical support for the staff gauge is most suitable. The following type of support has proved satisfactory for permanent installations: A section of 180 mm channel iron is embedded about 0.50 m in a concrete block and extended above the block to the maximum height required. The concrete block should extend well below the maximum expected frost penetration and at least 0.60 m below the minimum bed level of a natural stream. The top of the block should be 0.10 m below the lowest head to be measured. A staff of durable wood, 0.02 x 0.15 m, is bolted to the channel iron above the concrete block, and the enamelled gauge section is fastened to this staff with stainless steel screws.

For lined canals, the staff gauge can be mounted on the inclined canal side walls. Mounting the sidewall gauge in an irrigation canal is slightly different from placing a vertical gauge or a recorder. Often, the canal side slopes are not exactly as intended, either because the entire canal was somewhat tilted during construction or the wall has moved. If this occurs, and a premarked gauge which reads directly in m^3/s or ft^3/s is to be mounted, then the gauge, set to its zero end, could give erroneous values. To eliminate or reduce this kind of field error, the gauge should be set to the weir crest and mounted so that the most common head range is the most accurately located. The greatest errors will then occur at gauge readings that are seldom used.

The gauge can be mounted to the wall with lead or plastic anchors or other suitable concrete anchor-bolting systems. Wooden plugs in drilled concrete holes are not usually durable and should be avoided. Slotted holes in the gauge can be used to adjust the gauge to the proper final elevation, or the holes can be carefully measured and field drilled to match the anchor locations, which usually drift slightly from their intended locations. Always check the gauge after it has been fastened to ensure that it has not slipped. A second gauge point, say zero, should also be checked. This will

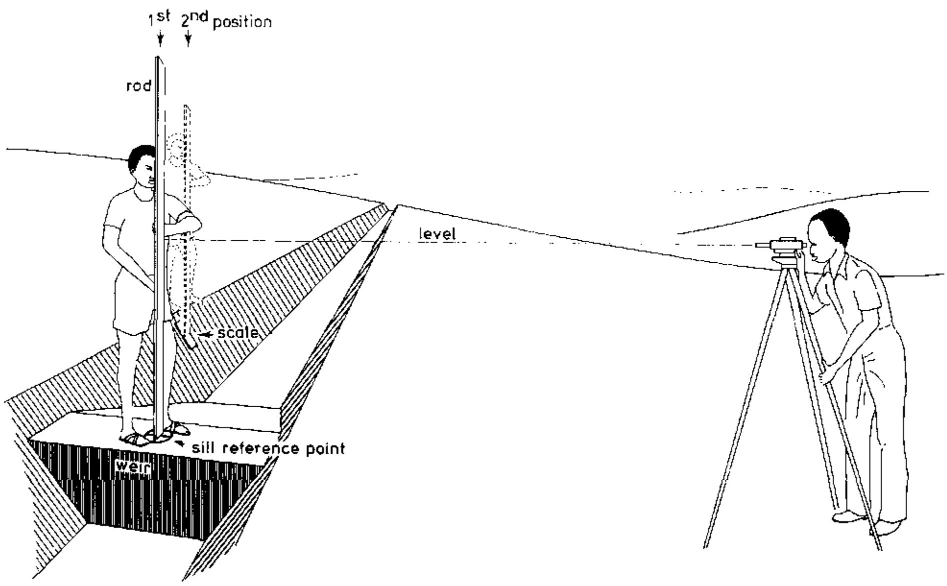

Figure 5.8 Stages of setting a gauge on a lined canal side slope

likely disclose any gross errors in arithmetic in placing the gauge, and will indicate whether the side-slope error is small or large. On flumes in an irrigation canal, an error in the zero reading of more than a centimetre would be cause for concern and should be carefully checked. If the side slope is very far off, it should be measured separately and a new gauge constructed.

The procedure to locate and mount the staff gauge correctly is as follows:

1 Determine the location of the gauging section by using Figure 5.1 and mark this section on the canal side slope.
2 With a surveyor's level, take a backsight on the sill crest at the sill-reference point (lst position) to get the sill-reference level. All rod readings are to ± 1 mm (0.003 foot) or more precise (see Figure 5.8).
3 Find the most common discharge, Q, to be measured and read the related h_l-value from the proper rating table.
4 Subtract this h_l-value from the taken backsight to find the value that must be read on the rod if it were to be placed on the mark for the above h_l- or Q-value on the scale.
5 Place the gauge on the side slope in approximately the right location. Set the rod on the gauge at the mark for the most common discharge. Move the gauge and rod up or down to the proper rod reading (2nd position in Figure 5.8).
6 Mark the gauge holes or slots and the gauge top and bottom on the canal wall. Drill the holes, secure the anchors, and tentatively attach the gauge to the canal wall.
7 Check the rod reading on the crest at the most common discharge, adjust gauge to correct location, and fasten securely.

The same procedure can be used for vertical staff gauges. If surveying equipment is not available, other methods similar to those used for zeroing recorders can be used.

6 Theory

6.1 Introduction

Two approaches can be used to determine the head-discharge relationship for flumes and weirs. One is to determine the discharge for an ideal fluid and multiply it by an empirical discharge coefficient, C_d, which is the ratio of the actual to ideal flow (Bos 1985).

$$C_d = \frac{Q}{Q_i} \tag{6.1}$$

The discharge coefficient, C_d, is the result of:
- Friction on the channel wall and bottom between the gauging station and the control section;
- The velocity profile in the approach channel and control section, and;
- Changes in pressure distribution caused by streamline curvature.

The other approach is to compute the effects directly by using a mathematical theory such as the one presented here. Thus, no empirical discharge coefficient is needed. In either case, the ideal flow is calculated as a base of reference or starting point.

6.2 Ideal-Flow Equations

For an ideal fluid at a constant flow, there is only one value of critical depth, y_c, for each value of energy head, H_c:

$$H_c = y_c + \frac{A_c}{2B_c} \tag{6.2}$$

where A_c is the wetted area at the control section and B_c is the water-surface width at the control section. As illustrated in Figure 6.1, we can write for the gauging station that

$$H_1 = h_1 + \frac{Q_i^2}{2g\,A_1^2} \tag{6.3}$$

where A_1 is the flow area at the gauging station and g is the acceleration due to gravity. For ideal fluid flow, there is no energy loss due to friction over the reach with accelerating flow, and thus $H_1 = H_c$, or

$$y_c + \frac{A_c}{2B_c} = h_1 + \frac{Q_i^2}{2g\,A_1^2} \tag{6.4}$$

This equation relates the upstream head, h_1, to the ideal flow, Q_i, for given cross-sectional shapes of the approach channel and the control section. The ideal flow, Q_i, can also be calculated by

$$Q_i = A_c\sqrt{2g\,(H_1 - y_c)} \tag{6.5}$$

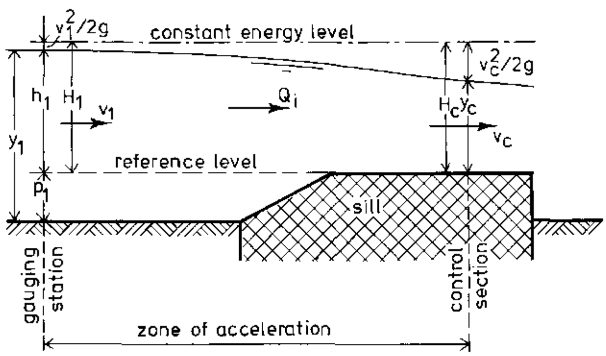

Figure 6.1 The energy level at the gauging station and at the control section for ideal flow

in which, according to Equations 6.2 and 6.4,

$$y_c = H_1 - \frac{A_c}{2B_c} \tag{6.6}$$

Combining Equations 6.5 and 6.6 gives

$$Q_i = \sqrt{g\frac{A_c^3}{B_c}} \tag{6.7}$$

This general equation is valid for all arbitrarily shaped control sections. The combined use of Equations 6.3, 6.6, and 6.7 is easy if simple equations exist for A_c and B_c in terms of y_c. For a trapezoidal control section, for example, these equations read

$$A_c = y_c\,(b_c + z_c y_c) \tag{6.8}$$

and

$$B_c = b_c + 2z_c y_c \tag{6.9}$$

The approach channel may also have any shape, but for the usual trapezoidal channel,

$$A_1 = y_1\,(b_1 + z_1 y_1) \tag{6.10}$$

where, as shown in Figure 6.1,

$$y_1 = p_1 + h_1 \tag{6.11}$$

Thus, for each combination of approach-channel and control-section shapes, Equations 6.3, 6.6, and 6.7 have unknown y_c, Q_i, and h_1. If any of these three is given, the other two can be solved by trial and error. The procedure for this trial-and-error solution is rather straightforward and starts with determining the range of h_1 values for which the appropriate discharge, Q_i, needs to be computed. Next, an initial guess is made for y_c in terms of h_1. The value of y_c ranges from $0.67H_1$ to $0.80H_1$ for a rectangular to a triangular control section respectively. Neglecting the velocity head, $v_1^2/2g$, we guess

$$y_c = 0.70\,h_1 \tag{6.12}$$

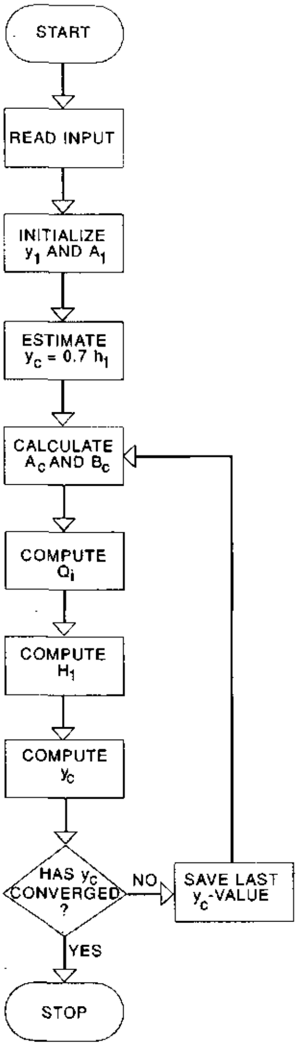

Figure 6.2 Flow diagram for ideal flow computations for given head

in all first trials. It is not worthwhile making a better guess of y_c for each computer run, since the trial-and-error method converges rapidly. Now, once y_c has been guessed, values of A_c, B_c, and Q_i can be computed, followed by H_l and y_c (from computed Q_i-value). If the new y_c-value equals the input y_c-value, then the computed Q_i is the flow rate for an ideal fluid matching the set h_l-value. After each trial, the new y_c-value replaces the previous y_c. Using the new y_c-value, a new series of calculations is made until the values match.

The procedure is illustrated in Figure 6.2. This method does not require an estimate of the velocity coefficient, C_v, for converting from H_l to h_l, since both H_l and h_l are

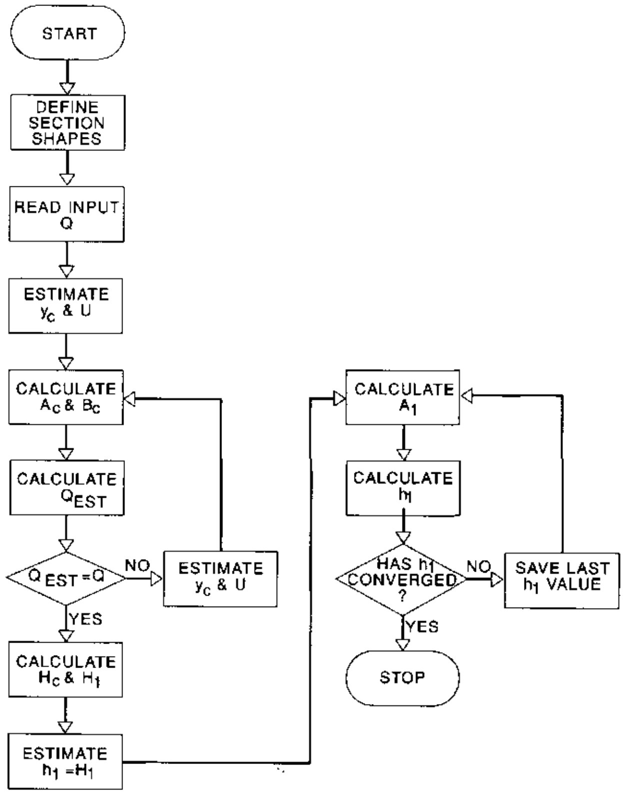

Figure 6.3 Flow diagram for ideal head calculations for given flow rate

used in the computation, and the energy heads are balanced. Also, the method starts with h_l rather than H_l, making it useful for the direct development of stage-discharge relationships.

Alternatively, if the value for Q_i is given, Equation 6.7 can be solved for y_c, iteratively, where A_c and B_c are functions of y_c. Then, H_l is found directly from Equation 6.6, and h_l is found from Equation 6.3, again iteratively. The related procedure is shown in Figure 6.3.

6.3 Energy Losses due to Friction

6.3.1 General

Because no ideal fluids exist in the real world, we must take the effects of friction into account. Evaluating the actual discharge through a flume requires that we take into account friction in the approach channel, converging transition, and throat. Friction in the diverging transition and tailwater channel does not affect the flume discharge, but it does affect the tailwater limit for maintaining modular flow (see Figure 6.4).

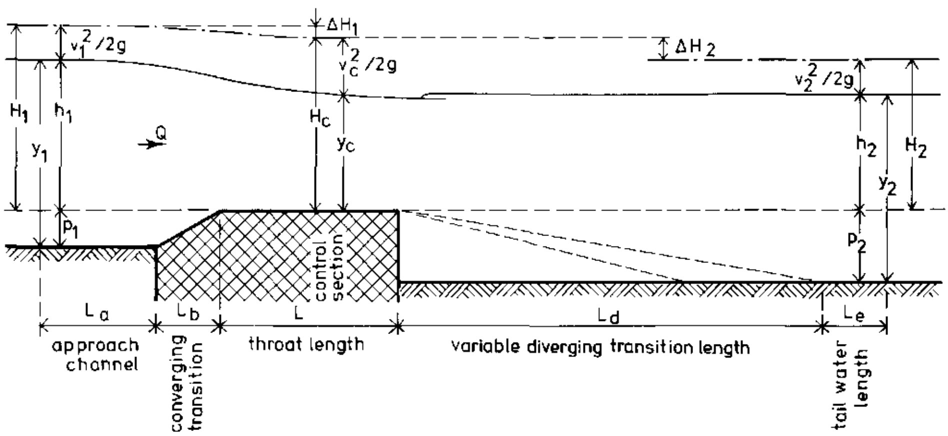

Figure 6.4 Illustration of terminology

Three methods are available for estimating friction losses through the flume: Manning, Chezy, and the boundary-layer drag method. FLUME uses the boundary-layer drag method. Ackers and Harrison (1963) reported that the effects of friction could be replaced with a change in flow area, represented by an imaginary displacement thickness (Harrison 1967). Replogle (1975) expanded upon their work and developed a flume model based on the boundary-layer drag theory, which, with minor modifications, is presented in this section.

6.3.2 Boundary-Layer Theory

For the boundary-layer analysis, it is assumed that the throat of the flume is one side of a thin and smooth flat plate held parallel to the fluid flow. The plate causes a drag on the fluid, which results in energy or head losses. The boundary layer is assumed to be 'tripped' by the break between the converging transition and the throat. Boundary-layer theory indicates that the flow in the boundary layer is not constant, but varies along the plate. The boundary layer starts out as laminar flow and then develops into turbulent flow, as shown in Figure 6.5. In reality, the transition from

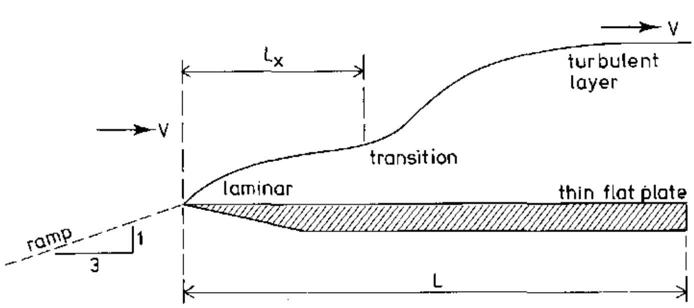

Figure 6.5 Transition from laminar to turbulent boundary layer

laminar to turbulent flow is gradual. For computing drag, however, the transition is assumed to be abrupt and to occur at a distance, L_x, from the entrance to the throat.

The combined drag coefficient, C_F, can be found by adding the relative drag coefficients for the laminar and turbulent parts of the boundary layer (Schlichting 1960). The turbulent part of the boundary layer acts as if the entire boundary layer were turbulent; thus the drag coefficient for the nonexistent turbulent boundary layer over L_x, namely $C_{F,x}$, must be subtracted from the turbulent drag coefficient over the throat length, L, $C_{F,L}$. The combined drag coefficient is then

$$C_F = C_{F,L} - \frac{L_x}{L} C_{F,x} + \frac{L_x}{L} C_{f,x} \tag{6.13}$$

where $C_{f,x}$ is the coefficient for the laminar boundary layer over L_x. The distance L_x can be developed from an empirical relationship for the Reynolds number of the laminar portion of the boundary layer.

$$RE_e = 350000 + \frac{L}{k} \tag{6.14}$$

where k is the absolute roughness height of the material. This Reynolds number is related to L_x by the definition

$$RE_x = v_c * \frac{L_x}{\upsilon} \tag{6.15}$$

where $v_c = Q/A_c$, being the average velocity of flow, and υ is the kinematic viscosity of the fluid. Similarly, the Reynolds number over the entire throat length, L, is

$$RE_L = v_c * \frac{L}{\upsilon} \tag{6.16}$$

Values for the turbulent drag coefficients are found from the following relationship (Harrison 1967), which was derived from Granville (1958):

$$C_{F,L} = \frac{0.554 C_{F,L}^{1/2}}{5.61 C_{F,L}^{1/2} - 0.638 - \ln[(Re_L\, C_{F,L})^{-1} + (4.84 C_{F,L}^{1/2} * L/k)^{-1}]} \tag{6.17}$$

Equation 6.17 can be used to determine $C_{F,x}$ by replacing $C_{F,L}$, Re_L, and L with $C_{F,x}$, Re_x, and L_x. This equation must be solved by trial and error, since $C_{F,L}$ (or $C_{F,x}$) appears several times.

The drag coefficient for laminar flow can be computed by the following equation suggested by Schlichting (1960):

$$C_{f,x} = \frac{1.328}{\sqrt{Re_x}} \tag{6.18}$$

If $Re_L < Re_x$, then the entire boundary layer is laminar and $C_F = C_{f,L}$, which is found from Equation 6.18, with Re_L replacing Re_x.

For a fully developed turbulent boundary layer, as would be expected in the approach channel, converging transition, diverging transition, and tailwater channel (Figure

6.4), the drag coefficient can be taken as 0.00235. The head loss for each part of the flume is found from the following equation

$$\Delta H_L = \frac{C_F L}{R} \frac{v^2}{2g} \tag{6.19}$$

where L is the length of each flume section considered, and R is the hydraulic radius. The combined head loss of the approach channel, converging transition, and throat is subtracted from the energy head at the gauging station to give the energy head in the critical section, $H_c = H_l - \Delta H_l$. Equation 6.6 changes to

$$y_c = H_1 - \frac{A_c}{2B_c} - \Delta H_1 \tag{6.20}$$

where

$$\Delta H_l = H_a + H_b + H_L \tag{6.21}$$

and the ΔH_a, ΔH_b, and ΔH_L correspond to the head losses in the approach channel, converging transition, and throat, respectively.

6.3.3 Roughness of Construction Material

The absolute roughness height for a number of materials typically used for flume construction is given in Table 6.1. An analysis of the effects of roughness height showed that a change of several orders of magnitude in the value of k produces less than an 0.5% (often less than 0.1%) change in discharge. Thus, a change in materials from smooth glass to rough concrete will have a minor effect on the discharge rating of the flume. This minor effect, however, should not be used as an excuse for sloppy or poor construction. If the surfaces in the control section have large undulations and irregularities, the real discharge can differ considerably from the theoretical value. Material roughness and construction tolerances should be regarded as different sources of potential error (see Section 4.6.2).

Table 6.1 Absolute roughness height of materials used in flume construction, k in metres

Material		Range of k
Glass		0.000 001 to 0.000 010
Metal,	Painted or smooth	0.000 020 to 0.000 10
	rough	0.000 10 to 0.001 0
Wood		0.000 20 to 0.001 0
Concrete,	Smooth trowelled	0.000 10 to 0.002 0
	Rough	0.000 50 to 0.005 0

6.3.4 Friction and Other Effects on the Range of H_l/L

A limitation was placed on the range of H_l/L values for which a reasonably reliable discharge rating can be obtained when an empirical discharge coefficient is used, namely,

$$0.1 \leq H_1/L \leq 1.0 \qquad (6.22)$$

This limitation was based on extensive laboratory data on a wide variety of flumes made from a variety of construction materials (Bos 1985). Within the range delimited by Equation 6.22, a good estimate of the discharge can be made from an empirical curve through the data. The data appear more closely grouped in the middle range (H_1/L = 0.35 to 0.70), with a range of about ±3% for the 95% confidence limits, and are more widely scattered at the extremes ($H_1/L = 0.1$ and $H_1/L = 1.0$), with a range of about ±5% for the 95% confidence limits. One of the major reasons for the wide scatter of data in the low range is friction. FLUME can accurately take frictional effects into account even when the value of H_1/L is as low as 0.05. One major reason for the wide scatter of data at the high range of H_1/L is streamline curvature. The laboratory data appear to deviate from the computer predictions above an H_1/L-value of about 0.5 because of streamline curvature, making the theoretical range of applicability of the model

$$0.05 \leq H_1/L \leq 0.5 \qquad (6.23)$$

A compromise can be reached between the two ranges to give a fairly realistic discharge range. Two factors are the basis of this compromise. First, the roughness of the construction materials changes over time. At low H_1/L values, these roughness changes can have a major influence on the flume calibration. Thus, while the model can predict these effects down to $H_1/L = 0.05$, possible changes in roughness restrict ordinary use of the model to $H_1/L = 0.070$. Up to $H_1/L = 0.70$, the effects of streamline curvature are minimal and have little effect on the discharge coefficient. A reasonable compromise between the two ranges for H_1/L is therefore

$$0.070 \leq H_1/L \leq 0.70 \qquad (6.24)$$

which we recommend. Within this range, FLUME calculates rating tables with an error of less than 2%. Outside this range, this error slowly increases to about 4% at $H_1/L = 1.0$. If a structure is to be designed with a high value of the ratio Q_{max}/Q_{min}, the full range of H_1/L-values should be used (see Section 4.3). In the output of FLUME, the value of H_1/L can be given as a function of the measured flow rate.

6.4 Velocity Profiles

The equations for ideal flow developed earlier in this chapter assume that the velocity profile in the throat is uniform. It may not be uniform, however, and so a velocity-distribution coefficient, α, is introduced to take non-uniform velocity profiles into account. The value of α is the ratio between the actual velocity head of the flow and the velocity head based on the average velocity of the flow, and it is always greater than unity. In long prismatic channels with a fully developed flow profile, α approaches a value of roughly 1.04 (Watts et al. 1967). For the approach channel, the velocity profile is assumed to be fully developed. This approximate value of $\alpha_1 = 1.04$ is used without further adjustment since the error in energy-head calculations resulting from an error in α_1 or in the velocity head is relatively small. For the control section, the velocity head is a much larger percentage of the total energy head, and the velocity distributions for critical flow tend to be more uniform. Thus, some correction for α_c at the control section is warranted. The following equation has been developed to estimate α for fully developed flow in wide channels (Chow 1959):

$$\alpha = 1 + 3\varepsilon^2 - 2\varepsilon^3 \qquad (6.25)$$

where $\varepsilon = (v_m/v)-1$, with v_m being the maximum flow velocity. For fully developed flow, ε can be approximated by

$$\varepsilon = 1.77\, C_{F,L}^{1/2} \qquad (6.26)$$

At the control section, the channel may not be sufficiently wide, and the flow profile may not be fully developed. Two additional factors are added to Equation 6.25 to take these deficiencies into account (Replogle 1974):

$$\alpha_c = 1 + [3\varepsilon^2 - 2\varepsilon^3]\,[1.5D/R - 0.5]\,[0.025L/R - 0.05] \qquad (6.27)$$

with $\quad 1 \leq (1.50\, D/R - 0.50) \leq 2$

and $\quad 0 \leq (0.025\, L/R - 0.05) \leq 1$

where D is the average or hydraulic depth and the other terms are as previously defined. This equation results in velocity distribution coefficients ranging from 1.00 to 1.04 for the ranges of conditions typically found in practice. This range is realistic, since several investigators have found nearly uniform velocity profiles at the control sections of long-throated flumes (Bos and Reinink 1981)

With the addition of the velocity distribution coefficient, Equation 6.7 becomes

$$Q = \sqrt{\frac{g\, A_c^3}{\alpha_c\, B_c}} \qquad (6.28)$$

and Equation 6.3 becomes

$$H_1 = h_1 + \alpha_1 \frac{Q^2}{2g\, A_1^2} \qquad (6.29)$$

where $\alpha_1 = 1.04$ and α_c is found from Equation 6.27.

6.5 Computing Actual Flow

Actual flow rates are computed by the same procedures that were used for ideal flow rates except that Equations 6.20, 6.28, and 6.29 replace Equations 6.6, 6.7, and 6.3, respectively. Values for ΔH_L are obtained from Equations 6.13 to 6.19, and the value for α_c is found from Equation 6.27. The ideal flow rate is computed first and is used as the initial guess for the actual flow rate. Next, the friction losses and velocity distribution coefficients are computed for the estimated discharge. Then, the actual flow rate (Equation 6.28) and the critical depth (Equation 6.20) are computed. The trial-and-error process is repeated (as for the ideal flow rate) until y_c converges. The resulting flow rate is checked against the flow rate for the previous values of ΔH_L and α_c. (The first time through, it will be compared with the ideal Q_i.) If the flow rate has not converged, ΔH_L and α_c are computed with the new Q and the process is repeated until the flow rate converges. This procedure is illustrated in Figure 6.6.

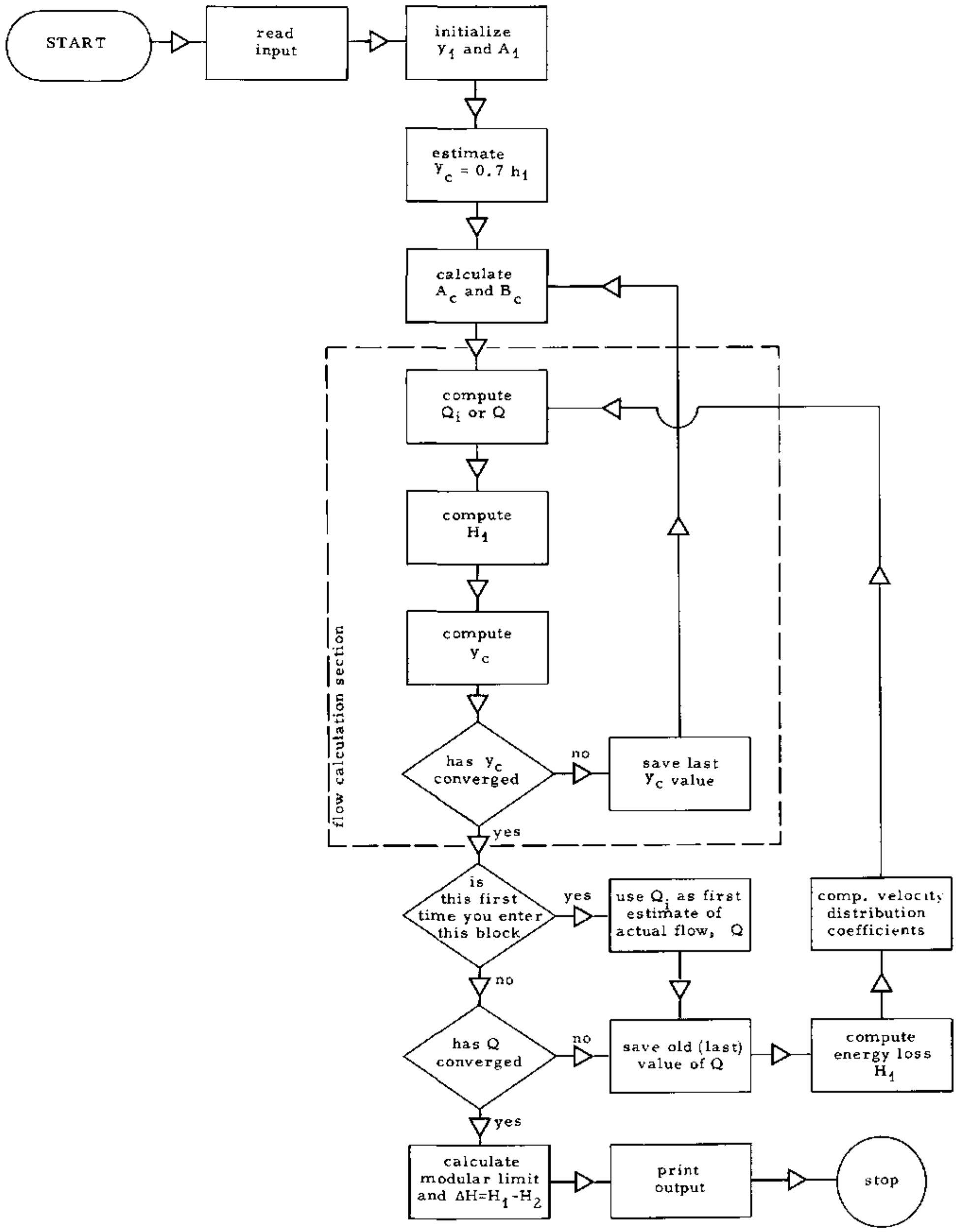

Figure 6.6 Flow diagram for computing discharge and modular limit

When Q is known, Equations 6.28 and 6.27 are solved iteratively for y_c and α_c, with equations for A_c and B_c as a function of y_c. H_c is found from Equation 6.2, H_l is found from $H_l = H_c + \Delta H_l$, and h_l is found from Equation 6.29, with A_l as a function of h_l. The ideal discharge for h_l can only be found after h_l is known, and is found by the above procedure for determining Q from h_l. This procedure is shown in Figure 6.7.

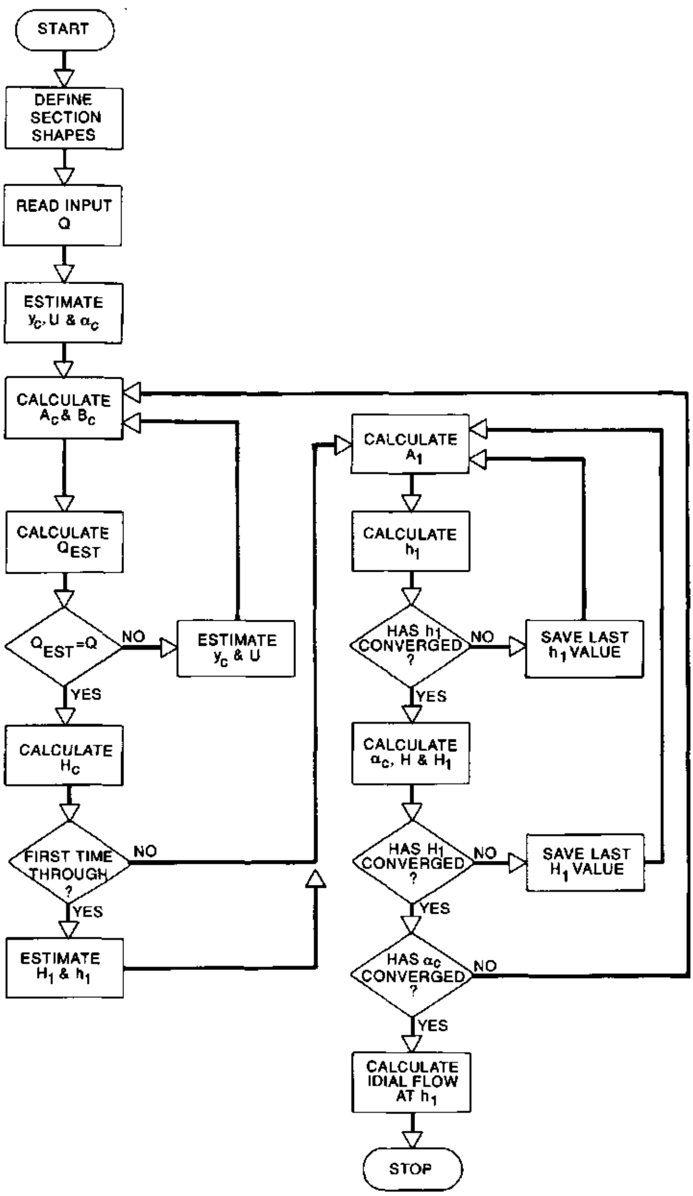

Figure 6.7 Flow diagram for computing head if the discharge is known

6.6 Contraction Needed for Critical Flow

6.6.1 Hydraulic Relations

If H_1 in Equation 6.5 is substituted by H_c, the actual flow through the control section equals

$$Q = A_c \sqrt{2g(H_c - y_c)} \tag{6.30}$$

Because the relation between H_c and y_c is known (e.g. for rectangular sections, $H_c = 1.5 y_c$), Equation 6.30 can be expressed in the form

$$Q = C1\, y_c^{U} \tag{6.31}$$

where $C1$ is a constant and U is the head-discharge exponent (1.5 for rectangular sections). A similar expression can be determined for the flow area, namely

$$A_c = C2\, y_c^{Ua} \tag{6.32}$$

The derivative of the flow area with respect to the water depth at any given depth is the top width; thus $B = dA/dy$. Hence, taking the derivative of Equation 6.32 and then substituting Equation 6.32 back in to remove $C2$ gives

$$B_c = \frac{U_a A_c}{y_c} \tag{6.33}$$

Substituting y_c/U_a for A_c/B_c into Equation 6.2 and substituting the resulting relation for $H_c - y_c$ into Equation 6.30 produces

$$Q = A_c \left(\frac{2g\, y_c}{2U_a}\right)^{0,5} \tag{6.34}$$

Substituting Equation 6.32 into Equation 6.34 for A_c and combining terms gives

$$Q = C2 \left(\frac{2g}{2U_a}\right)^{0,5} y_c^{Ua + 0.5} \tag{6.35}$$

Comparing this with Equation 6.31, we must have the same exponent on y_c. Hence:

$$U = U_a + 0.5 \tag{6.36}$$

Upon algebraic rearrangement of the Equations 6.30 to 6.36, the following relationships can also be found

$$U_a = \frac{B_c y_c}{A_c} \tag{6.37}$$

$$U = 0.5 + \frac{B_c y_c}{A_c} = \frac{B_c H_c}{A_c} \tag{6.38}$$

$$\frac{y_c}{H_c} = \frac{2U_a}{2U_a + 1} = \frac{2U - 1}{2U} \tag{6.39}$$

In addition, the average width can be defined as

$$\overline{B_c} = \frac{A_c}{y_c} = \frac{B_c}{U_a} \tag{6.40}$$

The state of flow in an open channel can be described by the Froude number, Fr, which can be defined as

$$Fr = \frac{v}{\sqrt{\frac{g\,A}{B}}} = \frac{Q/A}{\sqrt{\frac{g\,A}{B}}} \qquad (6.41)$$

At critical flow, the Froude number is unity. In the approach channel to a measuring flume, the Froude number will be less than unity. Dividing the approach channel Froude number by that for critical flow and squaring gives

$$Fr_1^2 = \left(\frac{A_c}{A_1}\right)^3 \frac{B_1}{B_c} \qquad (6.42)$$

Equation 6.42 shows that the upstream Froude number depends only on the ratios of areas and top widths between the approach and control sections. For a given approach channel, discharge and water depth (y_l), the top width, area, and Froude number can calculated. With this, Equation 6.42 defines the relation between A_l and A_c required to produce critical flow.

In previous work (Bos 1985, Clemmens and Bos 1992), the ratios A^*/A_l and B^*/B_l were used as a basis for design, where A^* and B^* are the area and top width at the control section based on the water surface elevation in the approach channel (i.e. if the water surface was horizontal). This relation is shown graphically in Figure 6.8. The mathematical expressions for areas and top widths follow from the above equations. Namely

$$A_c = C2\,y_c^{(U-0.5)} \qquad (6.43)$$

$$A^* = C2\,h_l^{(U-0.5)} \qquad (6.44)$$

$$B_c = \frac{U\,A_c}{H_c} \qquad (6.45)$$

$$B^* = \frac{(U-0.5)\,A^*}{h_1} \qquad (6.46)$$

The approach velocity coefficient, C_v, was also used. This coefficient corrects for not measuring H_l but h_l in the approach channel. By definition

$$C_v = \left(\frac{H_1}{h_1}\right)^U \qquad (6.47)$$

Substituting these relations into Equation 6.42 to remove B_c and A_c results in

$$Fr_1^2 = \left(\frac{2U-1}{2U}\right)^{2U} \left(\frac{A^*}{A_1}\right)^3 \left(\frac{B_1}{B^*}\right) C_v^2 \qquad (6.48)$$

This equation defines the first of two relations used in the design process of FLUME. The second relation is based on the definition of the total energy head:

$$H = h + \frac{v^2}{2g} = h + \frac{Q^2}{A^2\,2g} \qquad (6.49)$$

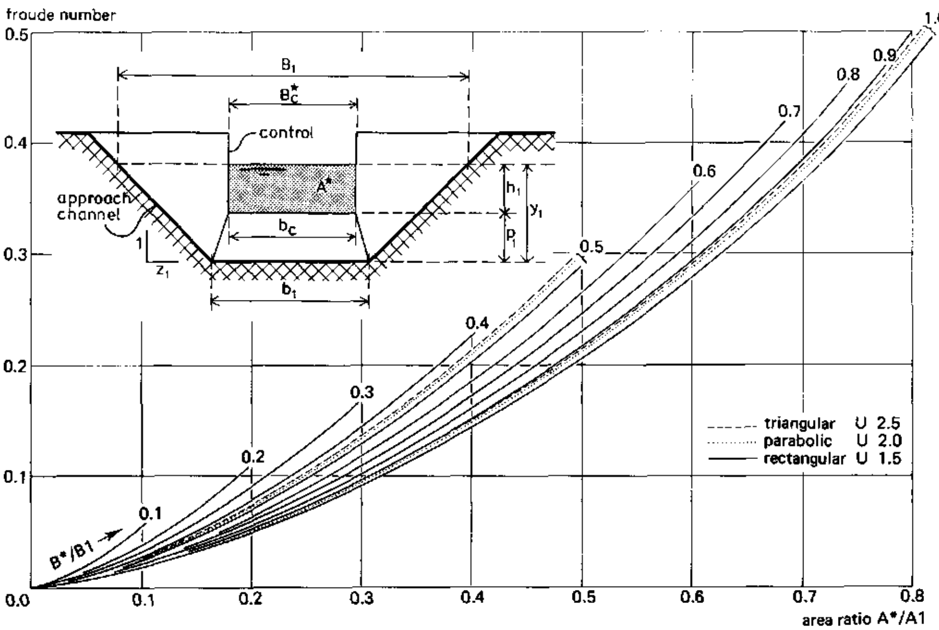

Figure 6.8 Relationship between the ratios A^*/A_1 and B^*/B_1 and the Froude number Fr_1

For the control section, combining this relation with Equation 6.30 gives

$$\frac{Q^2}{A_c^2\,2g} = \frac{A_c}{2B_c} \tag{6.50}$$

Substituting Equation 6.49 for H_1 into Equation 6.47 and then substituting for Q from Equation 6.50 gives, after rearranging,

$$C_v^{1/U} - 1 = \frac{A_c^3}{h_1\,A_1^2\,2B_c} \tag{6.51}$$

Substituting the relations from Equations 6.43 through 6.46 (to remove A_c, B_c, and h_1) into Equation 6.51 and rearranging results in

$$\left(\frac{A^*}{A_1}\right) = (2U-1)\left(\frac{2U}{2U-1}\right)^{2U}\frac{C_v^{1/U}-1}{C_v^2} \tag{6.52}$$

which is the second relation used in the design part of FLUME to calculate the contraction needed to create critical flow in the control section.

6.6.2 Design Procedure

There are many ways to produce a contraction. It can be provided from the side, from the bottom, or both (see Figure 1.2). And when considering the possible shapes of the control section (see Section 3.6.2), the number of possible solutions is thus infinite. In FLUME, it is assumed that the designer has specified the approach channel cross-sectional shape (with dimensions), the flow rate to be measured, and the upstream water depth desired for that flow rate after installation of the measuring structure (e.g. by specifying desired freeboard, existing tailwater levels, etc.). With these, the flow area, top width, velocity and Froude number in the approach channel can be calculated. In Equations 6.48 and 6.52, there are four unknowns; U, C_v, A^*/A_l, and B^*/B_l. If U and B^*/B_l were known, both equations could be solved iteratively for C_v and A^*/A_l. This would indicate the exact amount of contraction needed to create critical flow under the given upstream conditions.

The value of U, however, is not known and, for many shapes, is actually not constant with depth. It actually represents the slope of the tangent at a point on the head-versus-discharge curve on logarithmic paper. For common flume shapes, it falls between $U = 1.5$ for a rectangular cross-section and $U = 2.5$ for a triangular cross-section, with trapezoids, parabolas, etc., falling between. The general solution for determining the amount of contraction uses an iterative solution for the dimensions of the control section, since both B^*/B_l and A^*/A_l are allowed to change and since U is unknown.

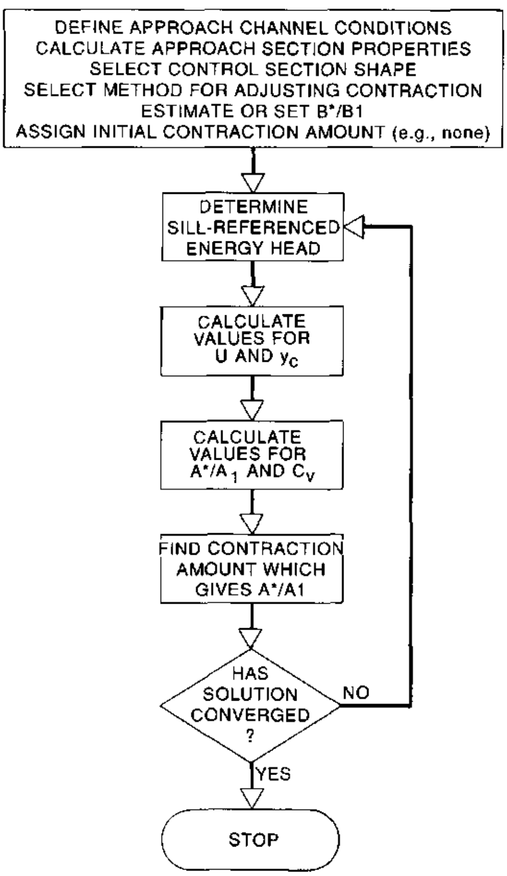

Figure 6.9 Schematic design procedure

The general procedure is:
1 Estimate U; $U = 2$ is a good initial guess for an unknown control section.
2 Compute y_c from Equation 6.39. FLUME uses $H_c = y_l$ as a rough first estimate.
3 Compute A_c and B_c from the cross-section shape and dimensions for the control section, and then compute U from Equation 6.38. This becomes the new estimate for U and the process is repeated until U converges.

This scheme converges very quickly. For some options, FLUME cannot design a flume or weir that has less contraction than the initial user-given structure. Because the designer does not usually have information on the needed sill height or side contraction, it is recommended that minimal contraction ($A^*/A_l \simeq 0.85$) be specified in the initial structure.

The user may also specify a control-section shape that is identical to the approach-section shape. FLUME simply alters the first guess so that the solution will converge. FLUME uses the user-selected method of contraction change to alter the control section to arrive at the needed ratio A^*/A_l. As the shape changes, the needed value of the ratio A^*/A_l changes slightly, so this becomes an iterative procedure. This procedure converges very rapidly as well (e.g. two or three iterations). See Figure 6.9.

6.7 Determining Acceptable Tailwater Levels

Maintaining modular flow requires that the energy head downstream from the structure be somewhat less than the energy head in the critical section for any given discharge. The energy head downstream is controlled by the channel conditions and structures downstream. Therefore, the flume must be designed so that the energy head in the critical section (and the approach channel) are high enough to ensure modular flow. The modular limit is the highest ratio between downstream and upstream energy head referenced to the flume sill or crest at which the flow is still modular (i.e. where the upstream head-discharge relation is not affected by downstream conditions). In Section 6.3, methods were given for determining the head or energy loss from the gauging station to the end of the flume throat. In this section, we shall discuss the energy losses downstream from the flume throat. These energy losses are of two types: 1) frictional losses, and 2) turbulent losses caused by the rapid expansion of flow. The frictional energy losses downstream from the flume throat are relatively small compared with the turbulent energy losses. Thus, some rough approximations are sufficient. The frictional energy losses can be estimated with sufficient accuracy by boundary-layer drag methods as discussed in Section 6.3.2. Just as for the approach channel, a constant drag coefficient of 0.00235 can be used. No information is available from which to estimate α_2, and since it also has little effect compared with the turbulent energy losses, it is assumed equal to unity. The total energy loss over the downstream part of the structure is

$$\Delta H_2 = \Delta H_d + \Delta H_e + \Delta H_k = \Delta H_f + \Delta H_k \tag{6.53}$$

where ΔH_f is the frictional loss downstream from the structure, ΔH_d is the frictional loss over the downstream transition, ΔH_e is the frictional loss over part of the tailwater channel, and ΔH_k is the energy loss due to the rapid expansion. The frictional losses are computed with Equation 6.19.

The energy loss or conversion for the downstream expansion (diverging transition) is

$$\Delta H_k = \xi \frac{(v_c - v_2)^2}{2g} \tag{6.54}$$

where ξ can be obtained from (adapted from Bos and Reinink 1981)

$$\xi = \frac{\log_{10} [114.59 \, Arctan \, (1/m)] - 0.165}{1.742} \tag{6.55}$$

where Arctan is in radians and m is the expansion ratio of the downstream diverging transition. For a flume with only a bottom contraction (e.g. the broad-crested weir), the expansion ratio is straightforward. It is simply the length of the transition divided by the sill height. For flumes with a side contraction or a combination of a side and a bottom contraction, determining a value for the expansion ratio is not quite as straightforward. The expansion of the flume bottom has a greater effect on the energy loss and recovery than the side contraction. Thus, for flumes with a sizable bottom contraction, the expansion of the bottom should be used in head-loss calculations. When the contraction is primarily from the side, the expansion ratio for the side walls should be used. Obviously, in some cases, both play a role. For these cases, there is no clear-cut way of determining which to use. However, observed data indicate that the values of ξ from Equation 6.32 are conservative and can be used for most structures. The minimum value of the side and bottom contraction ratios should be used.

The flume designer would usually like to find the maximum tailwater level and energy head, H_2, for which modular flow exists. These are found by solving for the minimum amount of energy loss through the structure. By solving for H_2, we obtain (see Figure 6.3):

$$\begin{aligned} H_2 = H_c - \Delta H_f - \Delta H_k &= H_c - \Delta H_2 \\ &= H_1 - \Delta H_1 - \Delta H_2 \end{aligned} \tag{6.56}$$

The friction loss in the throat downstream from the control section is contained in ΔH_l rather than in ΔH_f. Thus, ΔH_f includes only the friction losses in the diverging transition and tailwater channel. For a given flume with a known expansion ratio, channel geometry, upstream head, and flow rate, H_c and ΔH_f can be computed by the procedures given in Sections 6.2 to 6.4. Since the flow rate and channel geometry are known, v_2, and thus H_2 and ΔH_e, are functions of h_2. Therefore, Equation 6.33 can be solved by trial and error with one unknown, h_2. The modular limit is then computed as

$$ML = \frac{H_2}{H_1} \tag{6.57}$$

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Appendix I. Directory Maintenance

Hard Disk

FLUME creates a number of files on the hard disk that are necessary for its operation. These files are:

FLM.EXE	Main program
SETVAR.MEM	File containing various configuration variables
MPCONFIG.DBF	Database configuration file

If no flume database exists, FLUME will create one by generating the following files. If these files are erased or damaged, the user will have difficulty in retrieving their data.

NEW–STRUC.DBF	Defines database format used by FLUME
FLM.DBF	File containing list of flumes in database
IFLM.NTX	Index file for FLM.DBF
RATAB.DBF	Database containing all flume rating tables
IRATAB.NTX	Index file for RATAB.DBF

If a backup is made to a floppy disk or a backup disk is read from a floppy disk (e.g. created from another copy of FLUME on another machine), FLUME will create the following files on the hard disk:

IFLMBAK.NTX	Index file for backup flume database
RATABAK.NTX	Index file for backup rating table database

FLUME will operate without the following files, but they are used if available.

FLUMEHCR.DOT	Introductory picture of flume for Hercules Monitor
FLUMEVGA.DOT	Introductory picture of flume for VGA/EGA Monitor
INVERSE.CHR	Inverse character set

FLUME will also create one file for each flume in the FLUME database. These files will have the 8-character user-given name with a .DBF extension.

Backup Disk

When FLUME creates a backup, it creates two files, namely:

FLMBAK.DBF	File containing list of flumes which have been backed-up.
RATABAK.DBF	File containing rating tables for flumes in FLMBAK.DBF.

FLUME will also copy the file associated with each backed-up flume (i.e. username.DBF).