Chapter 3

Discharge

3.1 INTRODUCTION

Irrigation canals transport water from the water source to the farmers fields. The more fields that are served by a canal, the more water has to be transported. The rate at which water is transported by a canal is called its *discharge*, and the maximum discharge that any canal can transport is *canal capacity*. These are described here. The chapter also gives dimensions of canals as a function of their capacities.

3.1.1 What is discharge?

The discharge is the volume of water that is transported each second, and the volumes are expressed in litres (l) or in cubic metres (m^3) [1 m^3 = 1000 l], and the letter Q is commonly used as the symbol for the discharge.

FIGURE 8
Discharge in a canal

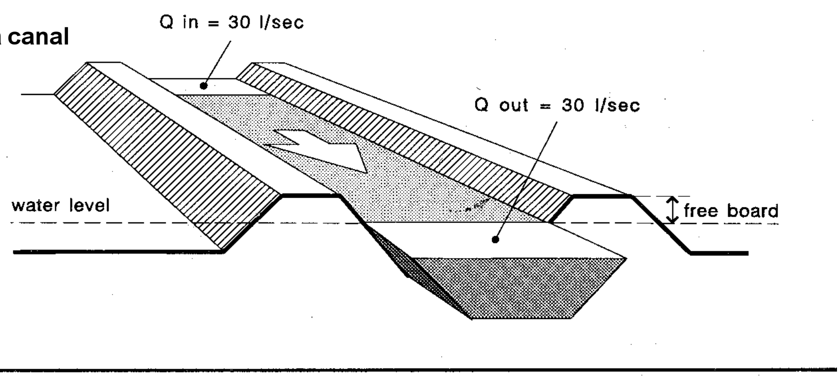


Figure 8 shows a short section of an irrigation canal which transports 30 litre of water every second (l/s). At the upper end of the section a volume of 30 l enters each second. In the same second a volume of 30 l leaves the section at the lower end. If, for example, a container with a volume of 30 l is placed at the end of this canal section, it will be filled every second. In symbols, this discharge is expressed as Q = 30 l/s.

3.1.2 Discharge and demand

The demands for irrigation water in a scheme are not constant during the irrigation season since they are largely affected by the amount of rainfall and by the water requirement of crops growing in the scheme. At the beginning of the season large amounts of water may be needed for land preparation, followed by a period of low water demand during the initial growth of the crop. As the crop develops and reaches full growth, water requirements will increase. Finally the demand decreases as the crop is maturing and ready for harvesting.

There are several ways of meeting the changing water demands of the farms:

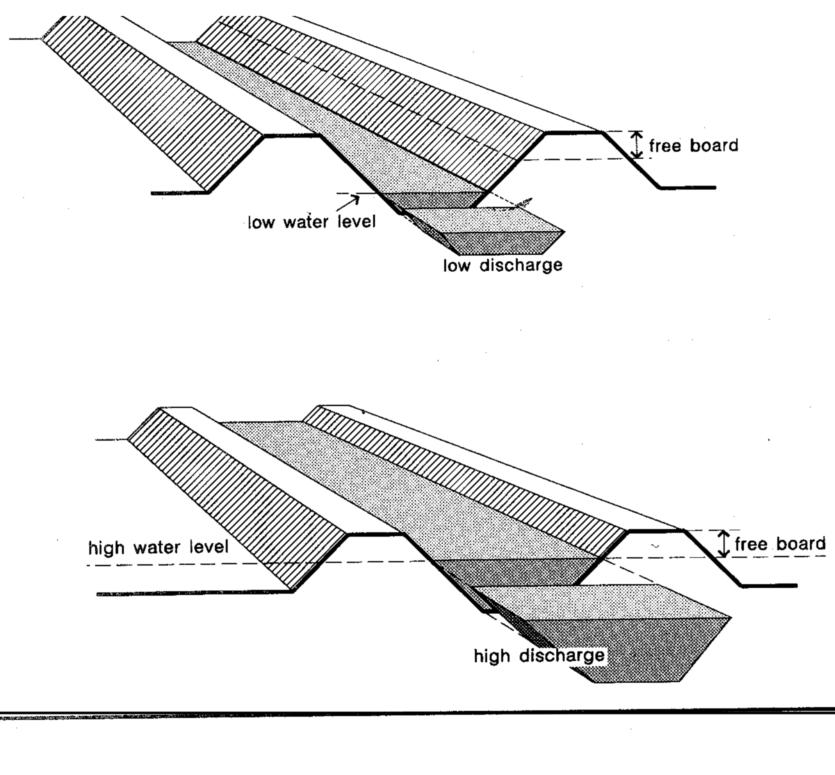
- the discharges in the canals can be adapted to the actual demands by manipulating the control structures or gate settings (See Training Manual 8: *Structures*);
- the duration of water delivery to the farms can be reduced or increased while discharges remain constant (not applicable in the case of continuous supply);
- the period between water deliveries , the interval , can be made longer or shorter, while the discharge and the duration of water delivery remain constant (not applicable in the case of continuous supply); or
- a combination of these.

3.1.3 Discharge control

Whichever of the options above is chosen to meet the actual water demands in an irrigation scheme, the water supply to the scheme and its distribution through the canals and over the fields need regulation and control. In order to supply the required amounts of water to the crops and to avoid waste by supplying too much, it is important to know the discharges in the canals. A procedure to estimate the discharge in a canal is presented in Section 3.2.

In general, in the same canal section, one can say that the water level is low for small discharges and it is high for large discharges, as shown in Figure 9.

FIGUE 9
Water level and discharge: low water level - low discharge; high water level - high discharge



As the discharge in a canal increases and the water level rises, there is a danger that the canal embankment will be overtopped. In order to avoid spillage of water and also to prevent the embankments from being damaged by overtopping water, a certain safety margin, called *minimum required free board*, is provided between the top of the canal banks and the maximum water level. In Figures 9, 11 and 12, the free board is indicated as *fb*. The concept of free board is explained in Section 3.2.2.

When the water level reaches the maximum water level, the discharge in the canal is the maximum allowed discharge, and is called canal capacity. Q_m, or Q_{max}, is commonly used as a symbol for canal capacity. Factors that influence the capacity of a canal are discussed in Section 3.3.

3.2 ESTIMATING THE DISCHARGE

The aim of good irrigation management is to obtain a correct flow division within the canal network and over the fields. This means that discharges in canals should meet the demand for water from the farms. A poor flow division may result in discharges being too high in some canals and too low in others, and could lead to water disputes between farmers. To achieve sufficient and equitable delivery of water to the fields it is useful to know the discharge in the canal. The discharge in a canal can be measured with or without a discharge measurement structure. Methods using structures are described in Training Manual 8, *Structures*, in this series. A method that does not require a structure is described below, and the flow measurement method described here is called the _floating method_. This method is a quick and cheap way to estimate discharge in a canal. However, this method is not very accurate and errors of at least 10% can be expected.

The method consists of estimating the average flow velocity (V), and measuring the area of the cross-section, called the 'wetted cross-section' (A). The discharge (Q) can be calculated by the following formula:

$$Q = V ´ A$$

where: Q is the Discharge in m^3/s;
V is the Average Flow Velocity in m/s; and
A is the area in m^2 of the Wetted Cross-section.

If one wants to know the discharge in l/s instead of m^3/s, the formula to use is:

$$Q = 1\,000 ´ V ´ A$$

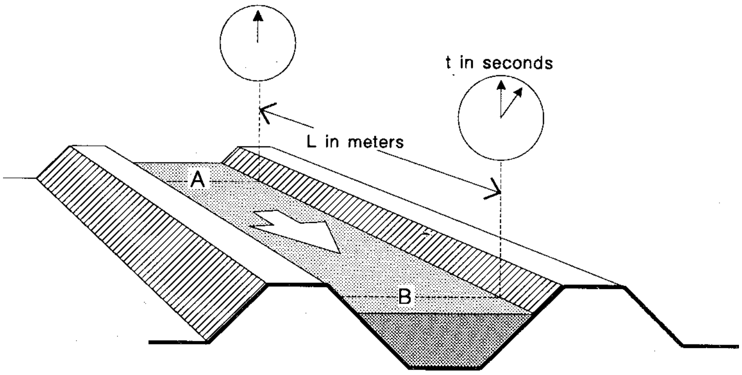
where Q is the Discharge in l/s;
1 000 is a factor to convert m^3 to l [1 m^3 = 1 000 l]; and
V and A are as before.

Section 3.2.1 describes a method to estimate the average flow velocity and Section 3.2.2 gives a method for determining the area of the wetted cross-section.

3.2.1 Average flow velocity

To estimate the average flow velocity, the flow velocity of the water at the surface , the surface velocity, V_s , is first determined. The surface velocity is determined by measuring the time it takes for a floating object, such as a stick, a bottle or a coconut, to travel through a previously measured distance of, say, 10 or 20 metres along the canal. The floating object should be placed

FIGURE 10
Measuring the surface velocity



in the centre of a canal and the time measurement should be repeated several times to avoid mistakes. The stretch of canal used for measurement should be straight and uniform, in order to avoid changes in the velocity and in the area of the cross-section, because any such variation reduces the accuracy of the velocity estimation. See Figure 10.

To compute the surface velocity, V_s, the selected length, L, is divided by the travel time, t:

$$V_s = L / t$$

where: V_s is the Surface Velocity in metres per second (m/s);
L is the distance in metres between points A and B; and
t is the Travel time in seconds between point A and B.

The surface velocity must be reduced in order to obtain the average velocity, because surface water flows faster than subsurface water. For most irrigation canals this reduction factor is about 0.75. The average velocity is therefore found from:

$$V = 0.75 \times V_s$$

where: V is the Average Flow Velocity in m/s;
0.75 is a constant, the Reduction Factor; and
V_s is the surface velocity in m/s found from the previous calculation.

EXERCISE 3

Question: What is the average flow velocity in a canal if:
- the measured length within a straight and uniform portion of the canal was 20 m [L = 20 m], and
- the time needed for a stick to travel along the measured length was 50 seconds [t = 50 s].

Solution:
Step 1 Find the surface velocity, V_s. $V_s = L / t = 20 / 50 = 0.40$ m/s.
Step 2 Find the average velocity, V. $V = 0.75 \times V_s = 0.75 \times 0.40 = 0.30$ m/s

3.2.2 Area of the wetted cross-section

General

To transport the canal discharge, various shapes and sizes of canal can be used, but the most commonly used shape is a trapezoidal cross-section. It can be used for every type of canal, and whether the channel surface is covered with waterproof material , a lined canal , or not , an unlined or earthen canal. However, rectangular and circular shapes are also used for lined canals. This manual covers only trapezoidal and rectangular shapes, as illustrated in Figures 11 and 12.

FIGURE 11
Rectangular canal

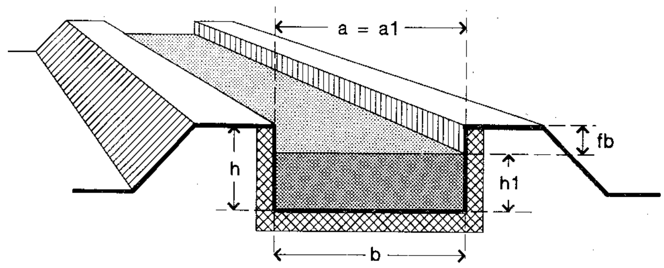
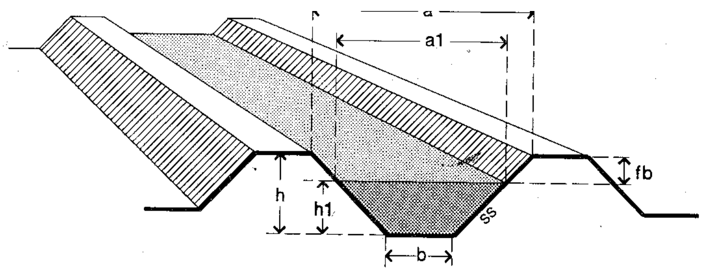


FIGURE 12
Trapezoidal canal



In both Figures 11 and 12 the following symbols are used: **a** is the Top Width, and for rectangular canals $\mathbf{a} = \mathbf{a_1} = \mathbf{b}$; $\mathbf{a_1}$ is the Water Surface Width; **b** is the canal Bed Width; **h** is the Height of the Embankment above the canal bed level; $\mathbf{h_1}$ is the depth of water; **fb** is the Free Board; and **ss** is the Side Slope (not applicable for rectangular canals)

The term free board (fb) was introduced in Section 3.1.3. In order to avoid overtopping of canal embankments and thus spillage of water and possible destruction of the banks by water erosion, a buffer is needed to accommodate fluctuations in water levels in canals. This buffer is called the free board. It is defined as the difference between the water level and the level of the crest of the embankment. The height of the minimum required free board depends on the water depth and on the material used for constructing the embankments. Embankments constructed using sandy material should have more free board than where clay has been used to make the embankments. When embankments are also used as pathways, free board should be increased to help protect them from destruction. As a rule of thumb, the following minimum required free board levels for small and medium canals should be respected:

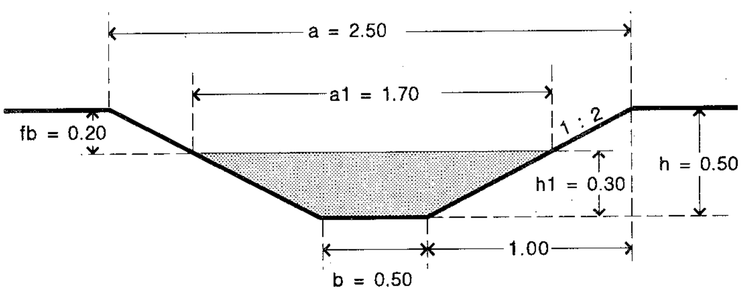
fb = 0.20 m for water depths of 0.40 m or less. The minimum height for an embankment should be the maximum water depth + 0.20 m, or $h = h_1 + 0.20$ m;

fb = 0.5 ′ water depth for water depths of 0.40 m or more. The minimum height of an embankment should be 1.5 x water depth, or $h = 1.5 \times h_1$.

The water surface width, a_1 depends on the side slope, *ss*. a_1 becomes closer to bed width (*b*) as *ss* becomes larger. The side slope depends on the material which is used for constructing the canal, and canals constructed with heavy clay can have steeper side slopes than those built with sandier material. Lined canals which are constructed from bricks or concrete can even have vertical side slopes. Typical side slopes for different canal materials are discussed in Section 4.2.3.

The side slope is expressed as a ratio, for example 1 in 2, 1 to 2, or 1:2. This means that the embankment rises one unit for each 2 units that it goes sideways, e.g., 10 cm up for every 20 cm out, or 50 cm vertical rise for each 100 cm horizontal displacement. This is illustrated with an example in Figure 13.

FIGURE 13
Side slope



The side slope in Figure 13 can be calculated from:

$$ss = \frac{\text{height of embankment}}{\text{width}^1 \text{ of embankment}}$$

$$ss = \frac{0.50}{1.00} = \frac{1}{2} = 0.5 \text{ or } ss = 1:2$$

Note:

$$ss = \frac{h}{(a-b)\ /\ 2} = 2 \times \frac{h}{a-b} = 2 \times \frac{0.50}{2.50 - 0.50} = 2 \times \frac{0.50}{2.00} = 2 \times \frac{1}{4} = \frac{1}{2};\ ss = 1:2$$

or:

$$ss = \frac{h_1}{(a_1-b)\ /\ 2} = 2 \times \frac{h_1}{a_1-b} = 2 \times \frac{0.30}{1.70 - 0.50} = 2 \times \frac{0.30}{1.20} = 2 \times \frac{1}{4} = \frac{1}{2};\ ss = 1:2$$

1 "width" is defined as the horizontal distance from the foot of the slope to the inner edge of the crest.

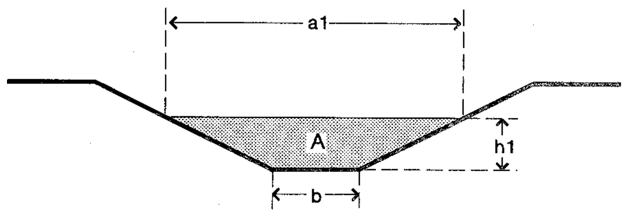
Calculating the area of the wetted cross-section

For measuring the flow with the floating method, the area of the wetted cross-section (A) should be determined for a selected straight and uniform portion of the canal. If the canal is trapezoidal this area is calculated from measurements of the bed width (b), width of the surface water (a_1) and the water depth (h_1) (See Figure 14), using the following equation:

$$A = \frac{(b + a_1)}{2} \times h_1$$

where:
A is area of wetted cross-section (m^2);
b is bed width (m);
a_1 is surface water width (m);
h_1 is water depth (m).

FIGURE 14
Trapezoidal cross-section

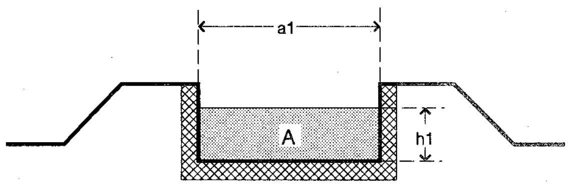


For rectangular canals the equation is as follows (see Figure 15):

$$A = a_1 \times h_1$$

where:
A is area of wetted cross-section (m^2);
a_1 is surface water width (m);
h_1 is water depth (m).

FIGURE 15
Rectangular cross-section



See also Sections 1.1.2 and 1.1.4 of Training Manual 1, *Introduction to irrigation*, in this series, and Figures 16, 17 and 18 below.

Cross-sections of unlined irrigation canals seldom have a regular shape. The bed width and the water depth may vary, even over short distances along the canal. The same applies for lined canals. However the changes in bed width and water depth in lined canals are less than in unlined canals. Because of these irregularities that are typical of unlined canals, the area of the cross-section should be measured several times to get the average area. In Exercise 7 an irregular shape of cross-section is measured.

FIGURE 16-A
Measuring the bed width

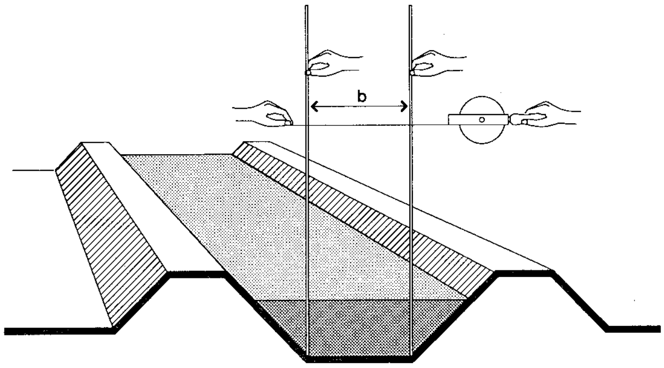


FIGURE 16-B
Measuring the surface water width

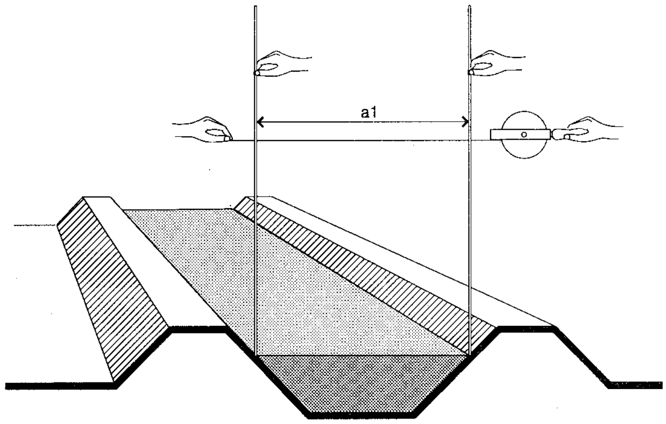
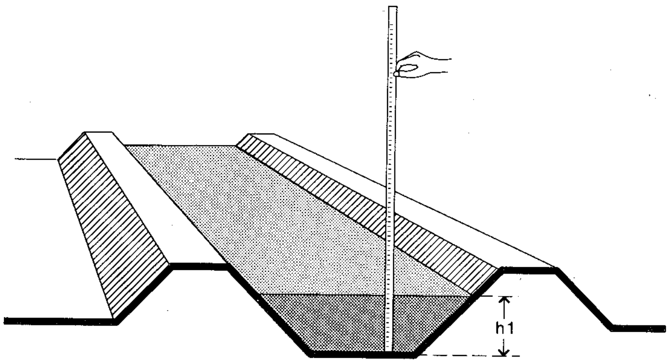


FIGURE 16-C
Measuring the water depth



EXERCISE 4

Question:
How wide are the bed width (b) and surface water width (a_1) and how deep is the water (h_1) of the canal with the slightly eroded cross-section shown in Figure 17?

Solution:

Step 1
Find the approximate location of the points where the bed of the canal starts to slope up into the canal banks. Poles or sticks can be used to locate these points. See Figure 18-A. Measure the distance between these points.

It is 0.44 m.

Step 2

Measure the width of the water surface. See Figure 18-B.

It is 0.96 m.

Step 3

Measure the water depth in the middle of the water surface.
See Figure 18-C.

It is 0.31 m.

FIGURE 17
Cross-section of an irregular canal

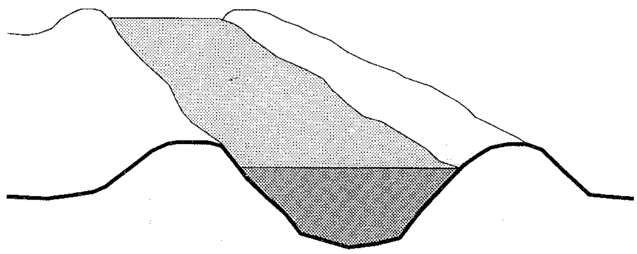


FIGURE 18-A
Measuring the bed width

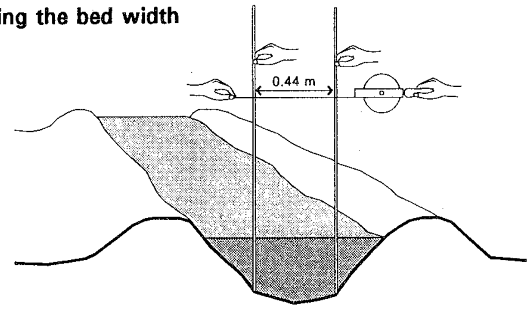


FIGURE 18-B
Measuring the surface water width

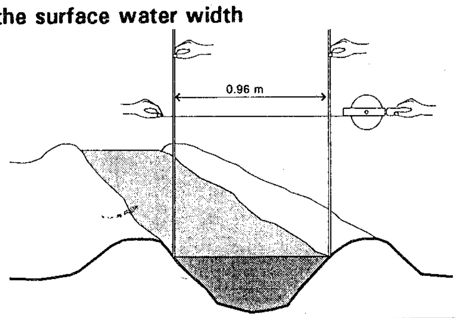
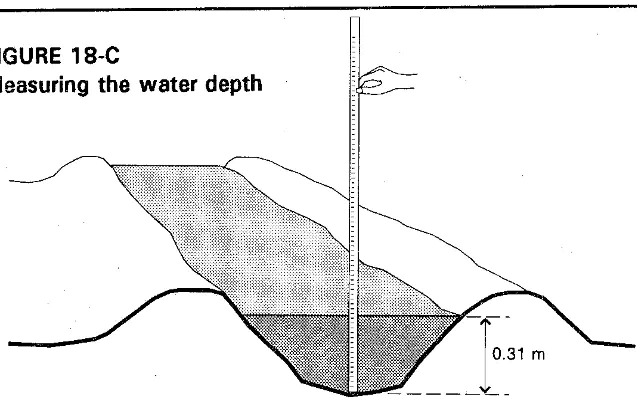


FIGURE 18-C
Measuring the water depth



3.2.3 Flow estimation procedure

The following presents the procedure for measuring the discharge using a floating object.

Equipment:
- Measuring tape at least 5 metres long
- 4 Stakes
- Stopwatch or watch capable of measuring time in seconds
- Floating object such as a bottle or coconut

Procedure:

Step 1 Select a straight section of the canal at least 10 metres long. The shape of the canal along this section should be as uniform as possible

Step 2 Place two stakes, one each side, at the upstream end of the selected portion of the canal. They should be perpendicular to the centreline of the canal. These correspond to point A in Figure 10.

Step 3 Measure 10 metres or more along the canal.

Step 4 Place two stakes at the downstream end of the selected section of the canal, also perpendicular to the centreline of the canal. These correspond to point B in Figure 10.

Step 5 Place the floating object on the centre line of the canal at least 5 m upstream of point A, and start the stopwatch when the object reaches point A.

Step 6 Stop the stopwatch when the floating object reaches point B, and record the time in seconds.

Step 7 Repeat steps 5 and 6 at least four times in order to determine the average time necessary for the object to travel from point A to point B. The object should not touch the canal embankment during the trial, but if it does the operation must be repeated and the time for the bad trial must not be included when calculating the average time.

Step 8 Measure the following in the selected canal section:
- the canal bed width, b
- the surface water width, a_1
- the water depth, h_1

The cross-section within the selected portion of the canal will usually not be regular, and so b, a_1 and h_1 need to be measured in several places to obtain an average value.

If working with a canal with a rectangular cross-section the surface water width a_1 will equal the bed width b.

Step 9 Calculate the surface velocity, V_s, and then the average flow velocity, V, using the equations given in Section 3.2.1:
- $V_s = L / t$, where t is the travel time is seconds, based on the average of four clear runs of the floating object, and
- $V = 0.75 \times V_s$.

Step 10 Calculate the wetted area of the cross-section A, using the formula from Section 3.2.2:

$$A = \frac{(b + a_1)}{2} \times h_1$$

(b, a_1 and h_1 are average values)

Step 11 Calculate the discharge, Q, in the canal, using the formula from section 3.2:

$$Q = V \times A \text{ m}^3/\text{s} \quad \underline{\text{or}} \quad Q = 1\,000 \times V \times A \text{ l/s}$$

EXERCISE 5

A straight and uniform portion of a trapezoidal canal was selected. Within this portion a length of 20 m was marked with pegs (Steps 1 to 4 above).

A coconut was used to determine the surface velocity (Steps 5 and 6). This was repeated 4 times with the following results (See Exercise 3):

t_1 = 50 seconds; t_2 = 52 s; t_3 = 53 s; t_4 = 53 s.

The wetted area of the cross-section has been measured 4 times (Step 8) (See Exercise 4:

b = 0.44; 0.42; 0.40 and 0.45 m
a_1 = 0.96; 1.02; 1.03 and 0.94 m
h_1 = 0.31; 0.28; 0.29 and 0.30 m

Question: What is the discharge Q?

Solution:

Step 1 Calculate the average travel time:
$t_{(average)} = (50 + 52 + 53 + 53) / 4 = 208 / 4 = 52$ seconds.

Step 2 Calculate the average values of b, a_1 and h_1:
$b_{1\,(average)} = (0.44 + 0.42 + 0.40 + 0.45) / 4 = 1.71 / 4 = 0.43$ m.
$a_{1\,(average)} = (0.96 + 1.02 + 1.03 + 0.94) / 4 = 3.95 / 4 = 0.99$ m.
$h_{1\,(average)} = (0.31 + 0.28 + 0.29 + 0.30) / 4 = 1.18 / 4 = 0.30$ m.

Step 3 Calculate the surface velocity V_s and the average flow velocity V:
Surface velocity is given by: $V_s = L / t$
L = 20 metres (marked); t = 52 seconds (Step 1)
Therefore $V_s = 20 / 52 = 0.38$ m/s.

Average flow velocity is given by: $V = 0.75 \times V_s$
Therefore $V = 0.75 \times 0.38 = 0.29$ m/s.

Step 4 Calculate the wetted area (A) of the cross-section, from Step 2:
The area is given by: $A = ((b + a_1) / 2) \times h_1$
b = 0.43 m; a_1 = 0.99 m; and h_1 = 0.30 m.
$A = ((0.43 + 0.99)/2) \times 0.30 = (1.42/2) \times 0.30 = 0.71 \times 0.30 = 0.213\ m^2$

Step 5 Calculate the discharge
Discharge is given by: $Q = V \times A$:
V = 0.29 m/s (from Step 3); $A = 0.213\ m^2$ (from Step 4)
Therefore $Q = 0.29 \times 0.213 = 0.062\ m^3/s$
or
$Q = 1\,000 \times V \times A = 1\,000 \times 0.29 \times 0.213 = 62$ l/s.

Answer: The discharge in the canal is 62 litres per second.

3.3 FACTORS AFFECTING THE MAXIMUM DISCHARGE

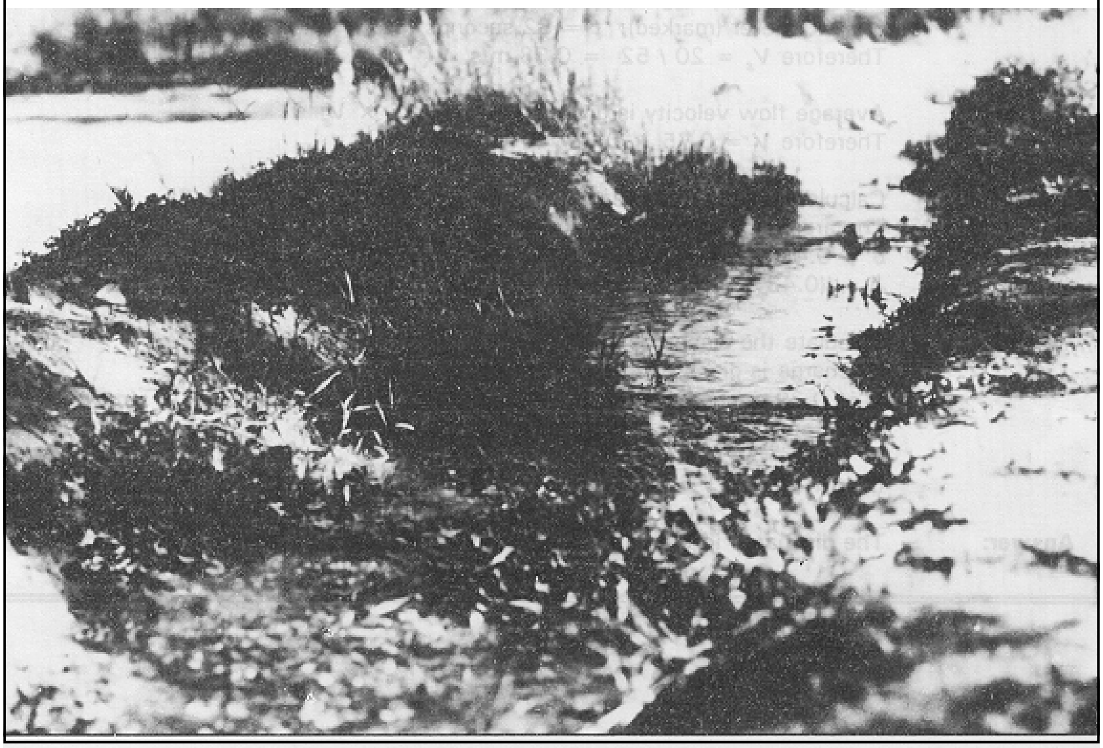
In order to avoid water levels in a canal being too high, the buffer between the water level and the top of the embankment should never be smaller than the minimum required free board for the canal. This means that each canal has a maximum water level which should be respected. Since water level and discharge are related, each canal has a maximum discharge that can safely be transported. This maximum discharge is also called canal capacity. Factors that determine the maximum discharge of a canal are:

- area of the maximum wetted cross-section,
- resistance to the flow, or roughness of the bed and sides, and
- bed slope or longitudinal slope in the direction of water flow.

3.3.1 Area of the maximum wetted cross-section

The area of the wetted cross-section has a great influence on the capacity of a canal. A big cross-sectional area permits a large flow to pass, and the flow velocity will also be higher when the area of the cross-section is larger. For example, if the bed width and the maximum water depth, while still respecting the minimum required free board, both increase by 10%, the capacity of the canal will increase by some 30%. If both increase by 20% or 30%, the capacity increases by some 60% and 100% respectively.

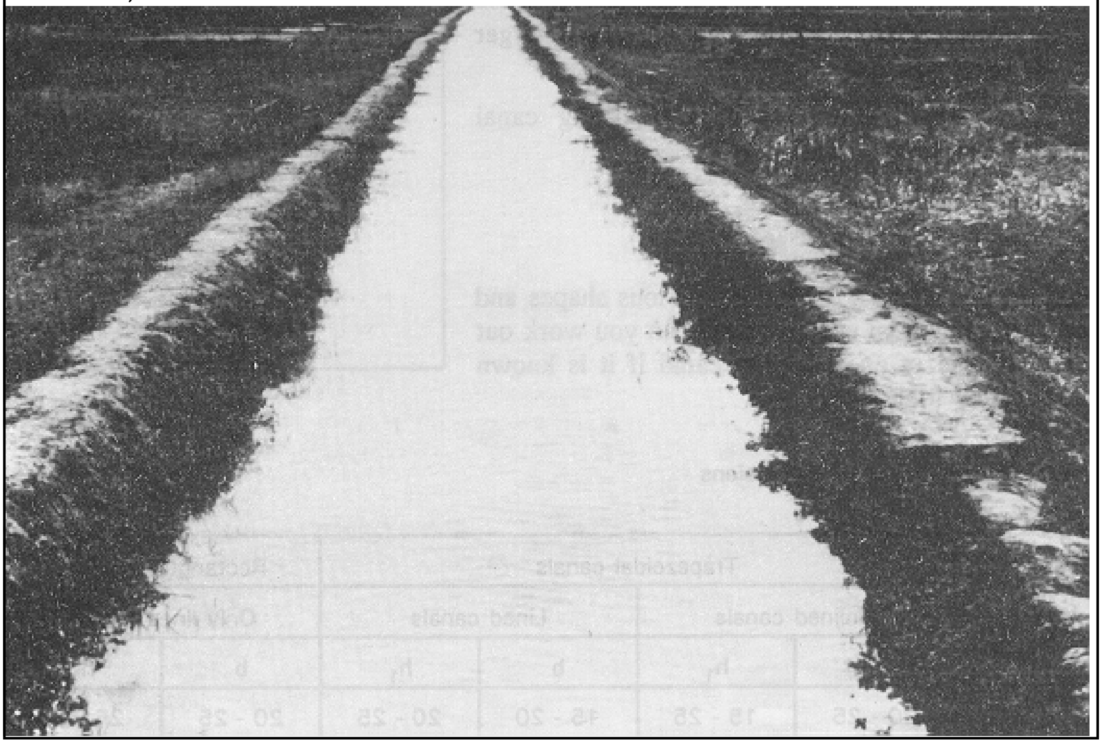
FIGURE 19
Rough, poorly maintained canal



3.3.2 Roughness of the canal bed and sides

The condition of the canal bed and sides also influences the capacity of a canal. In badly maintained canals, especially earthen canals, plant growth develops and becomes an obstacle to the free flow of water. The flow velocity and thus the capacity of a canal will be reduced. This

FIGURE 20
Smooth, well maintained canal



may be illustrated by comparing canals to roads: cars on rough roads will move more slowly than cars on good smooth roads. Similarly, water flows more slowly in a rough, poorly maintained canal than in a smooth, well maintained canal. An example of a rough canal is shown in Figure 19; a smooth, well maintained canal is presented in Figure 20.

If the canal in Figure 20 is allowed to develop plant growth and the canal becomes rough like the one in Figure 19, then its capacity may decrease by some 40%. In other words, the discharge which can safely be transported in the canal may be 40% less than before.

If a canal becomes rough, the flow velocity in the canal will decrease. Referring to the formula $Q = V' A$, it should be clear that for the same discharge and a smaller average flow velocity, the area of the wetted cross-section has to increase. Thus, due to a lower flow velocity, the water depth will increase and the canal will risk overtopping.

3.3.3 The longitudinal slope

The longitudinal slope of a canal influences its capacity too. The steeper the slope of a canal, the faster will flow the water and thus the larger will be its capacity. See Figure 21.

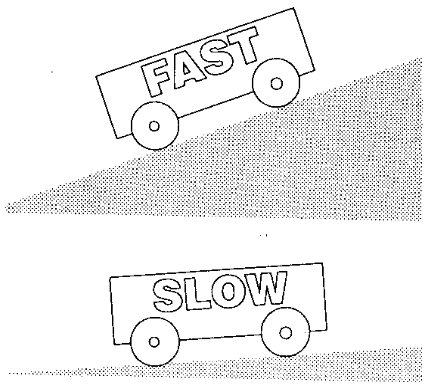
Figure 21 shows two lorries moving down hills. One hill has a steep slope, the other one is almost flat. The steeper the slope, the higher will be the speed of the lorry.

The longitudinal slope of a canal is generally expressed in percent or %. When the elevation of the canal bottom goes down 1 m with 1 000 m of canal length, the slope is 1/1 000, or 0.1%. (See Training Manual 1: *Introduction to irrigation*.) In general, the canal layout is made so that the longitudinal slope of a canal is somewhere between 0.05% and 0.15%, as discussed in Annex 3 of this Manual.

To illustrate the effect of canal slope on canal capacity, two canals with the same cross-section can be compared: one canal has a slope which is 10% steeper than the other. The canal with the 10% steeper slope will have a capacity which is 5% larger than the other canal.

Of course the slope of an existing canal cannot be made any steeper.

FIGURE 21
Longitudinal slope and velocity



3.4 CANAL DIMENSIONS

To transport the canal discharge, various shapes and sizes of canal can be used, so how can you work out the dimensions of an irrigation canal if it is known what capacity it should carry?

TABLE 1
Indicative values for canal dimensions

Capacity (l/s)	Trapezoidal canals				Rectangular canals	
	Unlined canals		Lined canals		Only lined canals	
	b	h_1	b	h_1	b	h_1
25	20 - 25	15 - 25	15 - 20	20 - 25	20 - 25	25 - 30
50	20 - 30	20 - 30	25 - 30	20 - 25	30 - 35	30 - 35
75	25 - 35	25 - 35	25 - 35	25 - 30	35 - 45	35 - 40
100	30 - 35	25 - 40	30 - 35	30 - 35	40 - 45	35 - 45
125	30 - 40	30 - 45	30 - 35	30 - 40	45 - 50	40 - 50
150	30 - 45	30 - 45	35 - 40	35 - 40	45 - 50	45 - 55
175	35 - 45	35 - 50	35 - 40	35 - 45	50 - 55	45 - 60
200	35 - 50	35 - 55	40 - 45	35 - 45	50 - 60	50 - 60

As was discussed in Section 3.3, the capacity of a canal is determined by the area of the wetted cross-section, the bed roughness and the longitudinal slope of the canal. Table 1 gives indicative figures for required bed widths and water depths for different canal capacities. The table covers both lined and unlined canals with trapezoidal cross-sections, and lined rectangular canals, and is valid for longitudinal slopes of between 0.05% and 0.15%; side slopes between 1:2 and 1:1 in unlined canals and between 1.5:1 and vertical in lined canals. Since different combinations of longitudinal slope, side slope and bed roughness , with smooth beds and sides without plant growth, or rough due to plant growth , are possible, margins of variation are given for the dimension of the cross-section of the canals.

The lower limits of bed width b and water depth h_1 are valid for canals which have a steep slope (close to 0.15%) and which are clean and well maintained. The higher limits are valid for canals with flatter slopes and which are covered with plant growth.

The table shows that for the same discharge, a larger canal size is required when it is not well maintained (rough surface) or the longitudinal slope is flat, and even more if both apply. For exact dimensions, detailed information is needed on the side slope, the longitudinal slope and on the roughness of bed and sides.