Chapter 1
Introduction to surface irrigation

Surface irrigation is the oldest and most common method of applying water to crops. It involves moving water over the soil in order to wet it completely or partially. The water flows over or ponds on the soil surface and gradually infiltrates to the desired depth. Surface irrigation methods are best suited to soils with low to moderate infiltration capacities and to lands with relatively uniform terrain with slopes less than 2-3% (FAO, 1974).

1.1. Components of a surface irrigation system

Figure 1 presents the components of a surface irrigation system and possible structures, which are described in Chapter 6. The water delivery system, shown in Figure 1, includes the conveyance system and the field canal system described below. The water use system refers to the infield water use system, showing one field in the block. The tail water ditch and the water removal system are part of the drainage system.

1.1.1. The water source

The source of water can be surface water or groundwater. Water can be abstracted from a river, lake, reservoir, borehole, well, spring, etc.

1.1.2. The intake facilities

The intake is the point where the water enters into the conveyance system of the irrigation scheme. Water may reach this point by gravity or through pumping. Intake facilities are dealt with during the design of headworks in Chapter 6. Pumping units are discussed in detail in Module 5.

1.1.3. The conveyance system

Water can be conveyed from the headworks to the inlet of a night storage reservoir or a block of fields either by gravity, through open canals or pipes, or through pumping into pipelines. The method of conveyance depends mostly on the terrain (topography and soil type) and on the difference in elevation between the intake at the headworks and the irrigation scheme. In order to be able to command the intended area, the conveyance system should discharge its water at the highest point of the scheme. The water level in the conveyance canal itself does not need to be above ground level all along the canal, but its starting bed level should be such that there is sufficient command for the lower order canals. Where possible, it could run quasi-parallel to the contour line. Design aspects of canals and pipelines are discussed in Chapter 5.

Although an open conveyance canal may be cheaper per unit length than a pipeline, the latter would need to be selected when:

- ❖ The water source is at lower elevation than the irrigation area, and thus pumping is required
- ❖ The topography of the land is very uneven, such that constructing an open canal could either be more expensive or even impossible (for example when crossing rivers and gullies)

A piped conveyance system also eliminates water losses through evaporation and seepage. An added advantage is that it does not provide the environment for water-borne disease vectors along the conveyance.

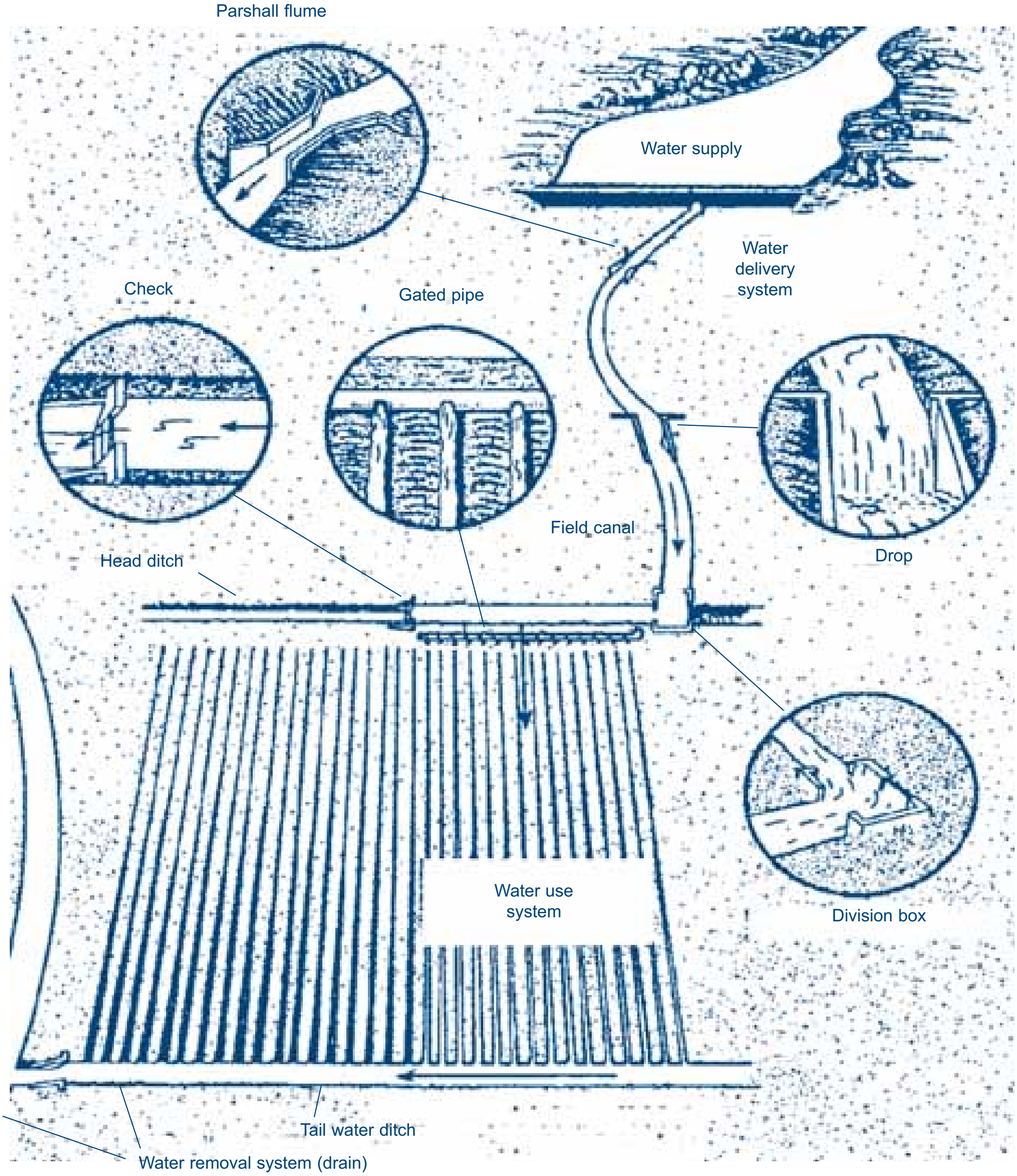
1.1.4. The water storage facilities

Night storage reservoirs (NSR) could be built if the irrigation scheme is large enough to warrant such structures. They store water during times when there is abstraction from the water source, but no irrigation. In Southern Africa it is common practice to have continuous flow in the conveyance system combined with a NSR located at the highest point of a block or the scheme. Irrigation would then be practiced during daytime using the combined flow from the conveyance system and the NSR. Depending on the size of the scheme one could construct either one reservoir located at the highest part of the scheme or a number of reservoirs, each located at the entrance of a block of fields. The conveyance system ends at the point where the water enters the reservoir.

1.1.5. The field canal and/or pipe system

Canals or pipelines are needed to carry the water from the conveyance canal or the NSR to a block of fields. They are called the main canal or pipeline. Secondary canals or pipelines supply water from the main canal or pipeline to the tertiary or field canals or pipelines, which

Figure 1
Typical components of a surface irrigation system (Source: Walker and Skogerboe, 1987)



are located next to the field. Sometimes no distinction is made between main and secondary and the canal or pipe system from the reservoir to the tertiary canal is called main canal or pipeline. The tertiary canals or the pipelines with hydrants are used to supply water to the furrows or borderstrips or basins. Where canals are used to deliver irrigation water, they should be constructed above ground level, as the water level in canals should be above field level for siphoning to take place. At times, water from the field canal is siphoned to a field earthen ditch from where the furrows, borderstrips and basins are supplied. When a piped distribution system is used, the gated pipe is connected to the hydrant and water is provided to the field from the gates of the gated pipe. Alternatively, a hose is connected to the hydrant to supply water to the field.

1.1.6. The infield water use system

This refers mainly to the method of water application to the field, which can be furrow, borderstrip or basin irrigation. These methods are described in detail in Chapter 2. It is important to note that the method of conveyance and distribution up to field level is independent of the selected infield irrigation method.

In irrigation system design, the starting point is the infield water use system as this provides information on the surface irrigation method to use, the amount of water to be applied to the field and how often it has to be applied. With this information, we can then work backwards or upstream to designing the field canal, distribution, storage, conveyance system and ultimately the intake facilities, and we can work forwards or downstream to determine the capacity of the drainage facilities.

1.1.7. The drainage system

This is the system that removes excess water from the irrigated lands. The water level in the drains should be below the field level and hence field drains should be constructed at the lower end of each field. These field or tertiary drains would then be connected to secondary drains and then the main drain, from where excess water is removed from the irrigation scheme.

1.1.8. Accessibility infrastructure

The scheme is to be made accessible through the construction of main roads leading to the scheme, and farm roads within the scheme.

1.2. The four phases of surface irrigation

When water is applied to the soil surface by any of the three surface irrigation methods (furrow, borderstrip or basin), it will infiltrate into the soil to the required depth in order to bring the soil back to field capacity. Using the borderstrip and basin irrigation method, the entire soil surface is wetted and the water movement through the soil is predominantly vertical. Using the furrow irrigation method, part of the soil surface is wetted and the water movement through the soil is both vertical and lateral.

The surface irrigation event is composed of four phases, as illustrated in Figure 2 and explained below.

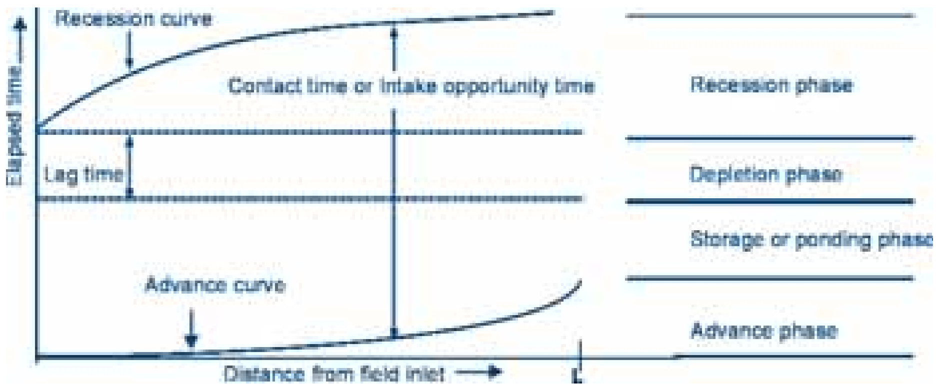
1.2.1. The advance phase

The advance phase begins when water is applied onto the field at the upstream end and ends when it reaches the downstream end of the field. The stream size applied at the head of the furrow, borderstrip and basin should be greater than the soil infiltration rate. This means that part of the water advances over the soil surface to the end of the field and part of the water infiltrates into the soil. The time between the start of irrigation and water advancement to the end of the field is called the *advance phase*. The advance curve in Figure 2 is the line showing the relationship between the elapsed time (on y-axis) and the advance distance (on x-axis).

1.2.2. The storage or ponding phase

When the water arrives at the tail end and the water supply at the head is continued, water floods the whole field. Some water continues infiltrating into the soil, some water ponds on the field and some excess water is collected as runoff. The time elapsed between the arrival of the water at the tail end and the stopping of the inflow at the top end is called the *storage phase* or *ponding phase*. This phase ends when the inflow at the head of the field is stopped.

Figure 2
Definition sketch showing the surface irrigation phases (Source: Basset *et al.*, 1980)



1.2.3. The depletion phase

After stopping the inflow at the head end, water may continue to pond on the soil surface for a while. Some water still infiltrates the soil, with the excess being collected as runoff. At a certain moment water will start receding from the head end. The time between the stop of the inflow at the head end and the appearance of the first bare soil that was under water is called the lag time or *depletion phase*.

1.2.4. The recession phase

After water starts receding from the head end, it continues to the tail end. The time when water starts to disappear at the head end until it eventually recedes from the whole field is called the *recession phase*.

The time-difference between the recession and advance curve is called the *contact time* or the *intake opportunity time*. This is the time in hours or minutes that any particular point in the field is in contact with water. Thus, by increasing or decreasing the contact time, one can, within limits, regulate the depth of water applied.

The following three basic principles are fundamental for surface irrigation, though the possibility of applying them depends a lot on the soil type:

i) The depth of infiltration varies in relation to contact time

ii) The contact time can be increased by using flatter slopes, increasing the length of run or reducing the stream flow; any one or a combination of these factors may be used

iii) The contact time can be decreased by steepening the slope, shortening the length of run or increasing the stream flow

1.3. Infiltration and contact time

Infiltration, which is the movement of water into the soil, is an important factor affecting surface irrigation in that it determines the time the soil should be in contact with water (the intake opportunity time or the contact time). It also determines the rate at which water has to be applied to the fields, thereby controlling the advance rate of the overland flow and avoiding excessive deep percolation or excessive runoff. The infiltration or intake rate is defined as the rate at which water enters into the soil, usually expressed in mm/hr.

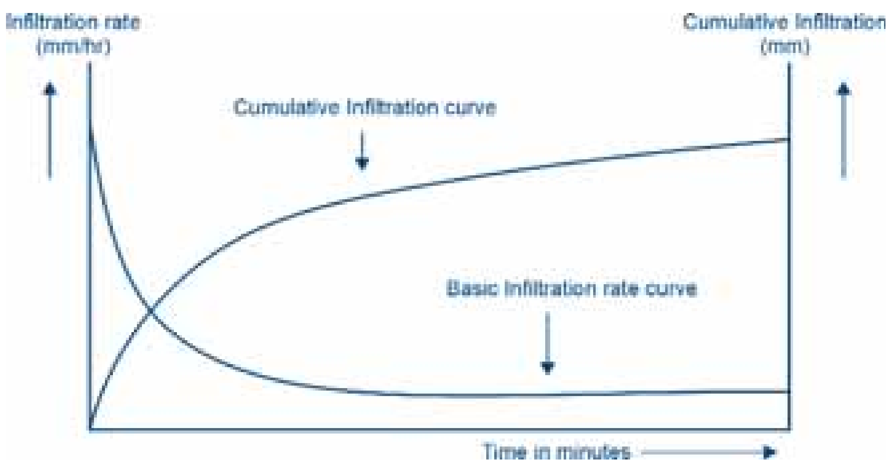
No matter where water infiltrates rapidly when it first arrives, after which it slows down until it reaches a steady state. This steady state is referred to as the basic infiltration rate, which is close to the value of the saturated hydraulic conductivity. When the basic infiltration rate is reached, the cumulative infiltration curve becomes a straight line and the basic infiltration rate curve becomes a horizontal line. This phenomenon is shown using a graph in Figure 3.

The infiltration rates of soils are influenced, among others, by the soil texture. Heavy soils have low infiltration rates by virtue of their small pore sizes, while light soils have high infiltration rates because of larger pore sizes. Some typical infiltration rates for different soil types are given in Table 1.

Table 1
Typical infiltration rates for different soils

Soil Type	Infiltration rate mm/hr
Sand	> 30
Sandy Loam	30-20
Silty Loam	20-10
Clay Loam	10-5
Clay	< 5

Figure 3
Basic infiltration rate and cumulative infiltration curves



The infiltration rate is a difficult parameter to define accurately, but it has to be determined in order to describe the hydraulics of the surface irrigation event. When planning a furrow irrigation scheme, one can determine the infiltration rate by two methods: the infiltrometer method and the actual furrow method. The former method can also be used to determine the infiltration rate for borderstrip and basin irrigation schemes.

1.3.1. Estimation of the infiltration rate using the infiltrometer method

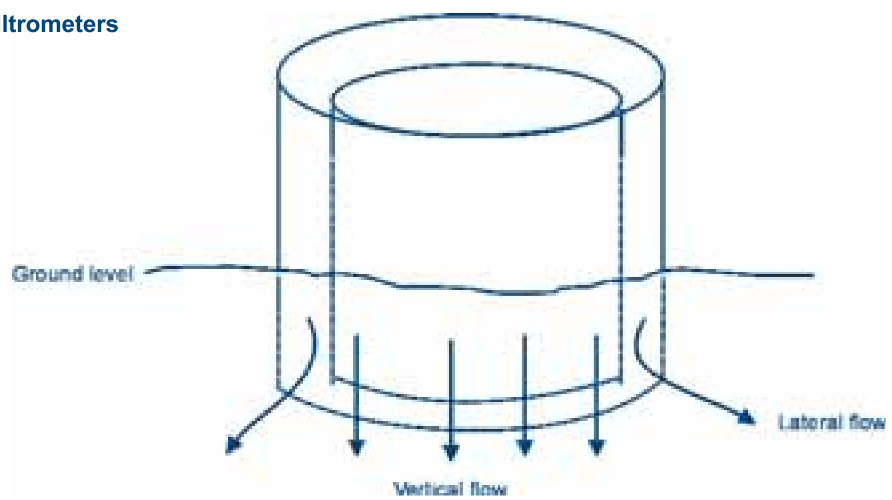
With this method, infiltration is measured by observing the fall of water within the inner cylinder of two concentric cylinders, with a usual diameter of 0.4 and 0.5 m and a height of about 0.4 m, driven vertically into the soil surface layer as illustrated in Figure 4. The outer ring acts as a buffer preventing lateral seepage of water from the inner one. This allows infiltration measurement from the inner ring to be representative of infiltration from the actual irrigation of a large area.

The procedure for installing the infiltrometer and for taking measurements is as follows:

- ❖ Select possible locations for three to four infiltrometers spread over the irrigation scheme and examine the sites carefully for signs of unusual surface disturbance, animal burrows, stones and so on, as they may affect the test results
- ❖ Drive the cylinder into the soil to a depth of approximately 15 cm by placing a driving plate over the cylinder, or placing heavy timber on top, and using a driving hammer. Rotate the timber every few pushes or move the hammer equally over the surface in order to obtain a uniform and vertical penetration
- ❖ Fix a gauge (almost any type) to the inner wall of the inner cylinder so that the changes in water level can be measured
- ❖ Fill the outer ring with water to a depth approximately the same as will be used in the inner ring and also quickly add water to the inner cylinder till it reaches 10 cm or 100 mm on the gauge
- ❖ Record the clock time immediately when the test begins and note the water level on the measuring rod
- ❖ The initial infiltration will be high and therefore regular readings at short intervals should be made in the beginning, for example every minute, after which they can increase to 1, 2, 5, 10, 20, 30 and 45 minutes, for example. The observation frequencies should be adjusted to infiltration rates
- ❖ After a certain period infiltration becomes more or less constant (horizontal line in Figure 3). Then the basic infiltration rate is reached. After reading equal water lowering at equal intervals for about 1 or 2 hours, the test can stop.
- ❖ The infiltration during any time period can be calculated by subtracting the water level measurement before filling at the end of the period from the one after filling at the beginning of that same period. For example, the infiltration between 09.35 hr and 09.45 hr in Table 2 is 100 - 93 = 7 mm, which is 0.7 mm/min or 0.7 x 60 = 42 mm/hr
- ❖ After the tests the cylinders should be washed before they become encrusted. This makes them easy to drive into the soil, with minimal soil disturbance, next time they are to be used

If the actual moisture conditions in the soil at the start of the infiltration test are low, it will take longer to reach the basic

Figure 4
Cylinder infiltrometers



infiltration rate compared to the same soil wherein the moisture is only slightly depleted. Preferably, tests should be carried out at the expected depletion level during irrigation.

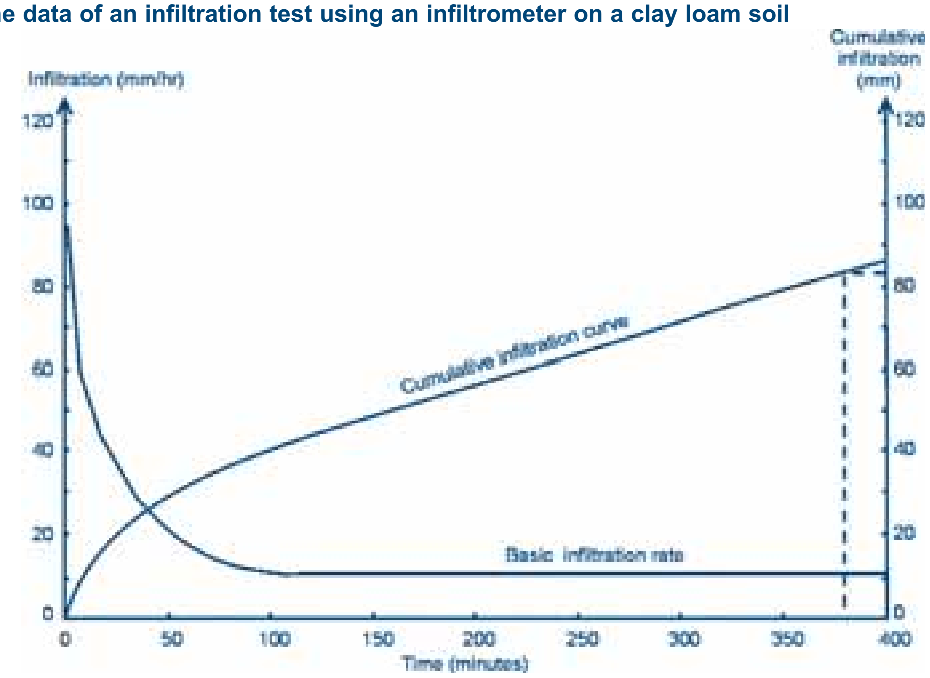
Results of an infiltrometer test on a clay loam soil are given in Table 2.

Table 2
Infiltration rate data from an infiltrometer test

Site location: Nabusenga **Soil type: Clay Loam** **Test date: 5 October 1990**

Watch reading (hr:min)	Time interval (min)	Cumulative time (min)	Water level reading before filling (mm)	Water level reading after filling (mm)	Infiltration (mm)	Infiltration rate (mm/min)	Infiltration rate (mm/hr)	Cumulative infiltration (mm)
	Start = 0							
09:25		0		100				Start = 0
	2				3.0	1.50	90.0	
09:27		2	97.0	100				3.0
	3				3.5	1.17	70.0	
09:30		5	96.5	101				6.5
	5				4.5	0.90	54.0	
09:35		10	96.5	100				11.0
	10				7.0	0.70	42.0	
09:45		20	93.0	99				18.0
	10				5.5	0.55	33.0	
09:55		30	93.5	100				23.5
	20				7.0	0.35	21.0	
10:15		50	93.0	100				30.5
	20				5.0	0.25	15.0	
10:35		70	95.0	100				35.5
	40				7.0	0.175	10.5	
11:15		110	93.0	101				42.5
	40				7.0	0.175	10.5	
11:55		150	94.0	100				49.5
	40				7.0	0.175	10.5	
12:35		190	93.0					56.5

Figure 5
Analysis of the data of an infiltration test using an infiltrometer on a clay loam soil



Example 1

The net peak crop water requirement for a scheme is 6.0 mm/day. The available moisture for the clay loam is 130 mm/m and depletion is allowed up to around 46%. The root zone depth is 0.70 m. After how many days should irrigation take place to replenish the soil moisture?

The moisture available to the crop in the root zone is 130 x 0.70 x 0.46 = 42 mm. The peak water requirement being 6.0 mm/day, after 42/6 = 7 days irrigation should take place to replenish the 42 mm soil moisture. This is equal to the net irrigation requirement.

Example 2

Assuming a field application efficiency of 50% in the previous example, what is the time required to replenish the 42 mm soil moisture?

The net irrigation requirement being 42 mm and considering a field application efficiency of 50%, the gross irrigation requirement is 42/0.50 = 84 mm. From the cumulative curve in Figure 5 it can be seen that the time required to replenish this depth of water is approximately 384 minutes.

If the field application efficiency increased to 65%, due to improved water management, the gross irrigation requirement would be 42/0.65 = 64.6 mm and the time required to replenish this depth would be reduced to 260 minutes.

It can be seen from Table 2, that the steady state has been reached somewhere between 70 and 110 minutes after the start of the test. From that moment on, the basic infiltration rate curve (Figure 3) will be a horizontal line and the cumulative infiltration curve will be a straight line. The results of the above test are graphically presented in Figure 5.

Examples 1 and 2 demonstrate the use of the intake rate in estimating the time required to replenish the soil moisture during irrigation.

The time required in Example 2 to replenish the required depth of water is called the contact time, which is the time the water should be in contact with the soil in order to have the correct depth of water replenished in the soil.

1.3.2. Estimation of the infiltration rate using the actual furrow method

With furrows, the infiltration rate and cumulative infiltration curve can also be determined as follows. Three adjacent furrows of a specific length, for example 30 m or 100 m, are wetted at the same time. Two measuring devices, such as for example portable Parshall flumes, are placed at the beginning and end of the middle furrow respectively, and the inflow at the top end and outflow at the tail end are measured simultaneously. The outer furrows function in the same way as the outer ring of the infiltrometer by preventing excessive lateral flow from the middle furrow. The infiltration in l/min (volume/time) can be converted into an infiltration in mm/hr (depth/time) by dividing it by the area covered by furrow. Table 3 and Figure 6 show the result for the same clay loam soil.

In this example, the furrow test starts at 14.00 hr with a continuous uniform flow of 98 l/min (1.63 l/sec) being discharged into the furrow. At the first recording of the inflow at the top, there is no outflow at the bottom end of the furrow. In this example, the outflow starts at 14.05 hr. From a recording of zero outflow there is a sudden outflow of 17 l/min (0.28 l/sec).

While the inflow remains constant, the outflow increases with time until the basic infiltration rate is reached at 15.10 hr. The infiltration is the difference between the inflow and the average of the outflow during a given time period. For example, between 14.20 hr and 14.30 hr, the inflow is 98 l/min and the average outflow is 56.7 l/min (={46 + 67.4}/2). Thus, the average infiltration rate over this period is 98 - 56.7 = 41.3 l/min. The average infiltration per period is calculated by multiplying the infiltration per minute by the time period. The sum of the infiltrations gives the cumulative infiltration.

The contact time can be determined from the cumulative infiltration curve, as shown in Figure 6. Considering the same data as used in Example 1 and 2, with a gross irrigation requirement of 84 mm, and considering a furrow length of 100 m and a furrow spacing of 0.75 m, the volume of water required per furrow is:

$$V = 0.084 \times 100 \times 0.75 = 6.300 \text{ m}^3 = 6\,300 \text{ litres}$$

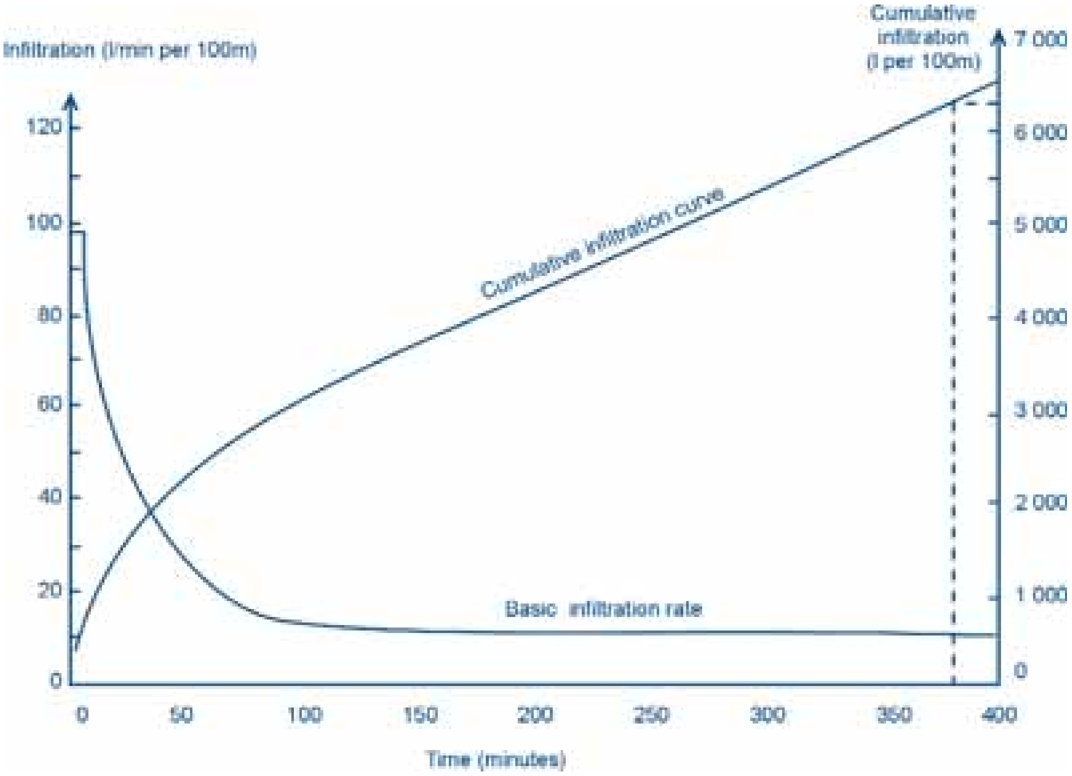
Figure 6 again gives a contact time of 384 minutes (x-axis) for this volume of 6 300 litres on the right-hand y-axis (cumulative infiltration).

Table 3
Infiltration rate measurement in a 100 m long furrow

Site location: Nabusenga **Soil type: Clay Loam** **Test date: 5 October 1990**

Watch reading (hr:min)	Time interval (min)	Cumulative time (min)	Water measurements: Inflow (l/min)	Water measurements: Outflow (l/min)	Intake rate l/min over 100 m	Intake (l/100 m)	Cumulative intake (l/100 m)
	Start = 0						
14:00		0	98.0	0			0
	5				98.00	490	
14:05		5	98.0	0 to 17			490
	5				67.00	335	
14:10		10	98.0	45.00			825
	10				52.50	525	
14:20		20	98.0	46.00			1 350
	10				41.30	413	
14:30		30	98.0	67.40			1 763
	20				26.25	525	
14:50		50	98.0	76.10			2 288
	20				17.51	375	
15:10		70	98.0	84.88			2 638
	40				13.12	525	
15:50		110	98.0	84.88			3 163
	40				13.12	525	
16:30		150	98.0	84.88			3 688
	40				13.12	525	
17:10		190	98.0	84.88			4 213

Figure 6
Analysis of the data of an infiltration test using actual furrows on a clay loam soil



1.3.3. Determination of optimum stream size and furrow length

In order to wet the root zone as uniformly as possible and to have minimum percolation losses at the top end of the field and minimum runoff at the bottom end of the field an appropriate stream size has to be chosen. As explained earlier, water flows from the top end of the field to the bottom end. This is called the advance stream (Figure 2). When water supply stops, the water moves away from the top of the field, which is called the recession of the waterfront. Usually the advance is slower than the recession because water infiltrates quicker in dry soil. Therefore, the top end of the field usually receives more water than the bottom end of the field and water will be lost through deep percolation. If the stream size is too small, it will take a long time before the water reaches the end of the field, therefore deep percolation will be high if the bottom end is also to receive enough water. On the other hand, if the stream size is too large, the waterfront will reach the bottom fast and runoff losses will occur, unless the stream size is reduced. Therefore the appropriate combination of stream flow size and length of borderstrip or furrow has to be selected.

As a rule of thumb, one can say that the stream size must be large enough to reach the end of the furrow in approximately one quarter of the contact time. This is called the one-quarter rule.

The optimum furrow length, or the optimum non-erosive stream flow in existing schemes with known furrow length, could be determined in the field with a test whereby the advance of selected stream sizes is measured in furrows. The results are plotted in a time-advance graph (Figure 7).

Following the above example, where the conditions would be such that a furrow length of 100 m would be preferable, the contact time is 384 minutes. Using the one-quarter rule of thumb, the water should reach the end of the furrow in 96 minutes (= 1/4 x 384). Different flows are brought onto the land and, using the plotted time-advance graph in Figure 7, the optimum furrow length would be 60 m for a flow of 0.5 l/sec and 100 m for a flow of 0.7 l/sec. If 0.7 l/sec is a non-erosive flow, which depends on the soil type and the actual state of the soil (which has to be checked in the field), the 100 m long furrow could be selected, which allows a more cost-effective layout. If the field shape allows it, a furrow should be as long as possible, in order to minimize the number of field canals that have to supply water to the field. This has a direct bearing on cost, since the cost increases with the number of canals to be constructed.

If the flow is not reduced once the water reaches the end of the furrow, a large runoff will occur. Therefore, the flow is usually reduced once or twice during an irrigation, such that runoff remains small. However, if the flow becomes too small, deep percolation losses at the top of the field might increase. The flow could be reduced by taking out siphons from the furrow. Field tests are usually carried out in order to make recommendations to farmers.

The discharge through siphons depends on the diameter of the siphon and the head. For drowned or submerged discharge, the head is the difference between the water level in the canal and the water level in the field (Figure 8a). For free discharge, the head is the difference between the water level in the canal from where the siphon takes the water and the outlet from the siphon (Figure 8b). Discharge can be altered by a change in pipe diameter or a change in the head (Table 4).

Figure 7

Time-advance graph for various stream flow sizes in a furrow

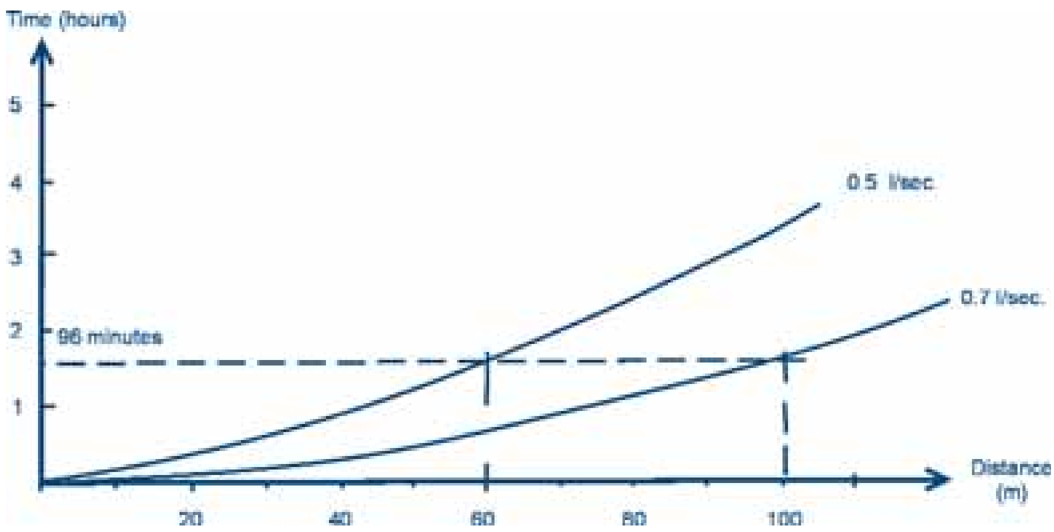


Figure 8
Determining the head (Source: FAO, 1988)

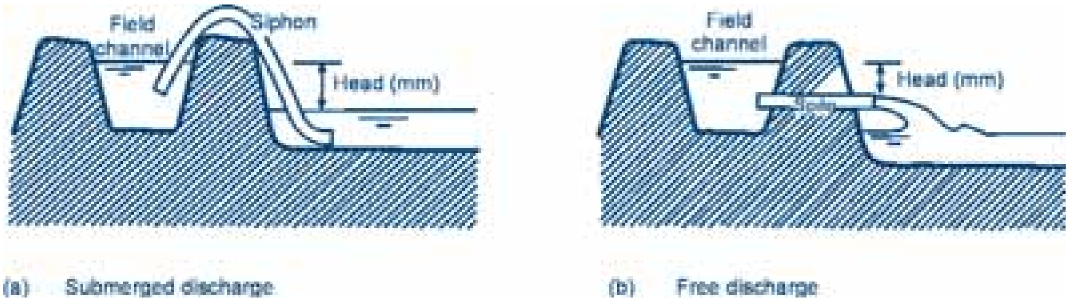


Table 4
Discharge for siphons, depending on pipe diameter and head (l/sec)

Pipe diameter (cm)	Head (cm)			
	5	10	15	20
2	0.19	0.26	0.32	0.73
3	0.42	0.59	0.73	0.84
4	0.75	1.06	1.29	1.49
5	1.17	1.65	2.02	2.33

1.3.4. Determination of optimum stream size and borderstrip length

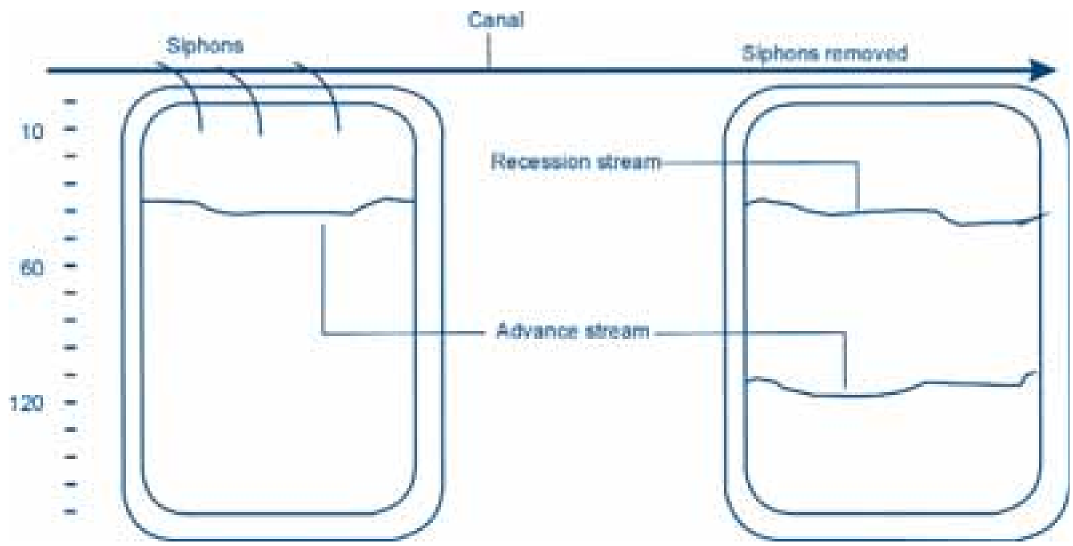
As in the case of furrow irrigation, it is important to use the right stream size for the soil and land slope and to stop the flow at the right time so that just enough water infiltrates into the soil to satisfy the required irrigation depth. If the flow is stopped too soon, there may not be enough water on the borderstrip to achieve the required irrigation depth at the bottom end of the borderstrip. If the water is left running for too long, there may be large runoff losses. As a rule of thumb, the water supply is stopped when the waterfront reaches between 2/3 and 3/4 of the borderstrip length. On clayish soil, the inflow is usually stopped earlier than on loamy soils, while on sandy soils the water could almost cover the whole borderstrip length before the flow is stopped. New irrigators can rely on the general guidelines given in Table 5 to decide when to stop the flow. The actual field cut-off times should then be decided through field experience.

Table 5
Guidelines to determine when to stop the water supply onto a borderstrip

Soil Type	Stop the flow when advance reaches the following portion of borderstrip
Clay	Two thirds of total length
Loam	Three quarters of total length
Sand	Almost end of borderstrip

Where possible, it is recommended to carry out field tests to determine the best borderstrip length. To do this, a borderstrip is marked with pegs at 10 m interval along its

Figure 9
Advance and recession of water on a borderstrip



length. A selected discharge is then brought onto the strip and the advance of the water is measured, which is the time that it takes for the water to pass through pre-determined distances along the borderstrip length (Figure 9). When the desired volume of water has been delivered to the borderstrip, the flow of water from the canal onto the borderstrip is stopped. As explained above, usually this is done before the water has reached the end of the border. From that moment on, time is taken when the end of the water flow passes through the pre-determined distances. This is called the recession of the water. For a fixed irrigation depth, the total volume desired depends on the size of the borderstrip and thus is larger for a longer borderstrip in cases where the width is the same.

Having measured the time and the distance of the advance and the recession of the water, the advance and recession curves can be drawn. If testing, for example, two different borderstrip lengths, the total volumes of water to be applied are different, leading to two different recession curves, since the inflow is stopped later when the borderstrip is longer. Table 6 shows the data for the advance stream, which is the same for both recessions and the data for recession 1 and recession 2.

The advance curve and the two recession curves have been presented as graphs in Figure 10.

Table 6 shows the data for the advance stream, which is similar for both recession streams. The same table also shows the results from the two separately conducted recession tests. From these data it can be seen that the supply of test 2 was stopped earlier (at 404 minutes) when compared to test 1 (at 464 minutes). The volume brought onto the land during test 1 had completely infiltrated in the soil at 744 minutes, covering the first 130 m of the border. In test 2 all water disappeared after 624 minutes and the required depth had been applied to the first 100 m.

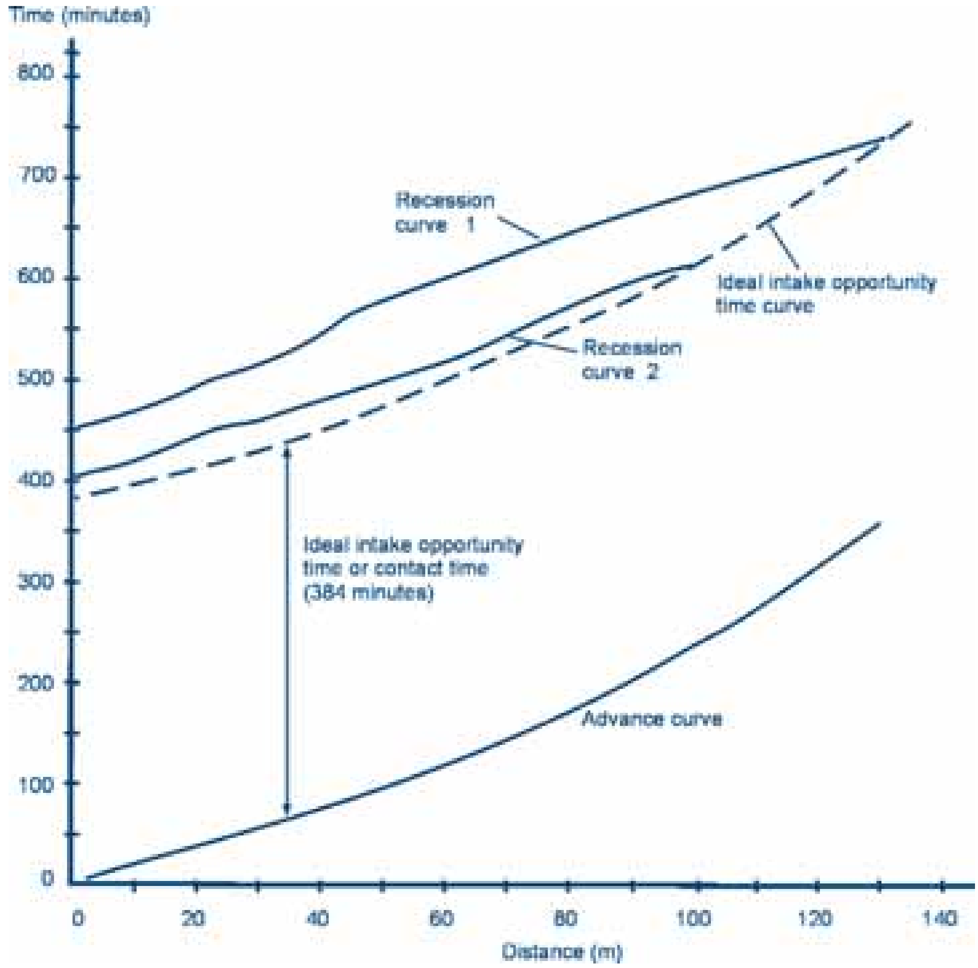
Considering Example 2, where a contact time of 384 minutes was calculated, the ideal intake opportunity time curve was drawn in Figure 10 to be parallel to the advance curve derived from the data of Table 6. The same figure presents the two recession curves derived from the data of Table 6. The closer a recession curve is to the ideal intake opportunity time curve the more efficient the water application. Looking at the two recession curves, it is clear that recession curve 2 is situated closer to the ideal intake opportunity curve than recession curve 1. Recession curve 1 shows that over-irrigation took place, especially over the first 100 m reducing later on for the remaining 30 m. While some deep percolation is also indicated by the position of recession curve 2, this is much less than that demonstrated by recession curve 1. Hence the designs should be based on 100 m length of border.

Table 6
Measurement of water advance and recession distance and time on a borderstrip

Advance (m)	Time (min)	Recession 1 (m)	Time (min)	Recession 2 (m)	Time (min)
0	0	0	464	0	404
10	20	10	476	10	422
20	38	20	494	20	444
30	57	30	524	30	464
40	80	40	560	40	480
50	100	50	586	50	502
60	120	60	608	60	524
70	143	70	629	70	554
80	170	80	649	80	582
90	205	90	671	90	604
100	240	100	692	100	624
110	278	110	710	110	
120	315	120	726	120	
130	350	130	744	130	

Figure 10

Advance and recession curves for different borderstrips lengths, needing different total volumes of water to be applied



Chapter 2
Criteria for the selection of the surface irrigation method

Surface irrigation methods refer to the technique of water application over the soil surface in order to wet it, either partially or completely. They do not bear any reference to the conveyance and field canal or distribution system. Three surface irrigation methods can be distinguished:

- Furrow irrigation
- Borderstrip irrigation
- Basin irrigation

Good surface irrigation practice calls for efficient water management to be achieved through:

- Distributing the water evenly in the soil
- Providing adequate water to the crops (not too much, not too little)
- Avoiding water wastage, soil erosion and salinity

2.1. Furrow irrigation

A furrow irrigation system consists of furrows and ridges. The water is applied by means of small channels or furrows, which follow a uniform longitudinal slope. The method is best suited to row crops such as maize, potatoes, onions, tomatoes, etc.

Water can be diverted from the field canal or the tertiary canal into furrows by means of siphons placed over the side of the ditch or canal bank and be allowed to flow downstream along the furrow (Figure 11). The water level in the canal must be raised to a sufficient height above the level of the furrows by using a piece of wood, check plates, or canvas filled with sand. This creates a head difference between the water level in the field ditch and the furrow, which is necessary for the water flow. Water can also be diverted into furrows through gated pipes or hoses connected to a hydrant fitted on buried pipes.

Figure 11
An example of a furrow irrigation system using siphons (Source: Kay, 1986)

The water is gradually absorbed into the soil and spreads laterally to wet the area between the furrows. The amount of water that infiltrates the soil at any point along the furrow depends on the soil type and the period during which the water is in contact with the soil at that particular point. This is known as the contact time or the intake opportunity time (see Chapter 1). With furrow irrigation, water is mainly lost by deep percolation at the head end of furrow and runoff at the tail end. Furrows can be used on most soil types, although coarse sands are not recommended since percolation losses, especially at the top end, would be high because of high infiltration rates. Soils that crust easily are especially suited for furrow irrigation, since the water does not flow over the ridge, which means that the soil in which the plants grow remains friable.

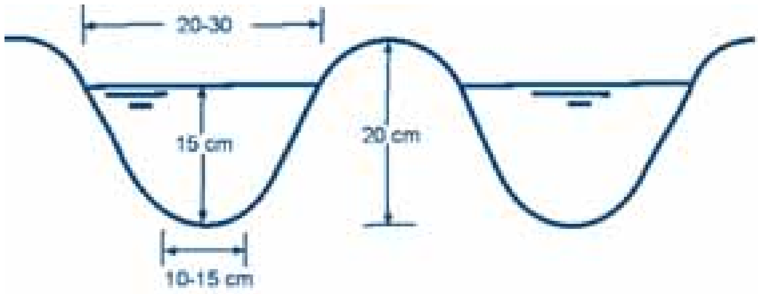
Furrow design is an iterative process that should consider the shape of the furrow, the spacing between furrows, with the furrow length determined, amongst other factors, by the stream size to apply and its application time, the soil type and the slope.

As mentioned by Michael (1994), rational procedures for predicting the water front advance and tail water recession in furrows, which are applicable to field designs, have not been developed. Various workers have proposed a number of quasi-rational procedures with varying degrees of adaptability. In the absence of more precise information on predicting the water advance and recession in furrows, general principles regarding stream size, furrow length and furrow slope to obtain efficient irrigation are followed in field design.

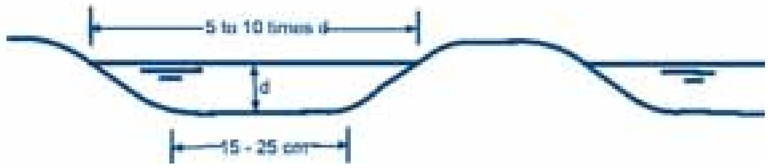
2.1.1 Furrow shape

The furrows are generally V-shaped or U-shaped in cross-section and are 15-30 cm deep and 25-40 cm wide at the top. The shape of the furrow depends on the soil type and

Figure 12
Furrow shape depending on soil type

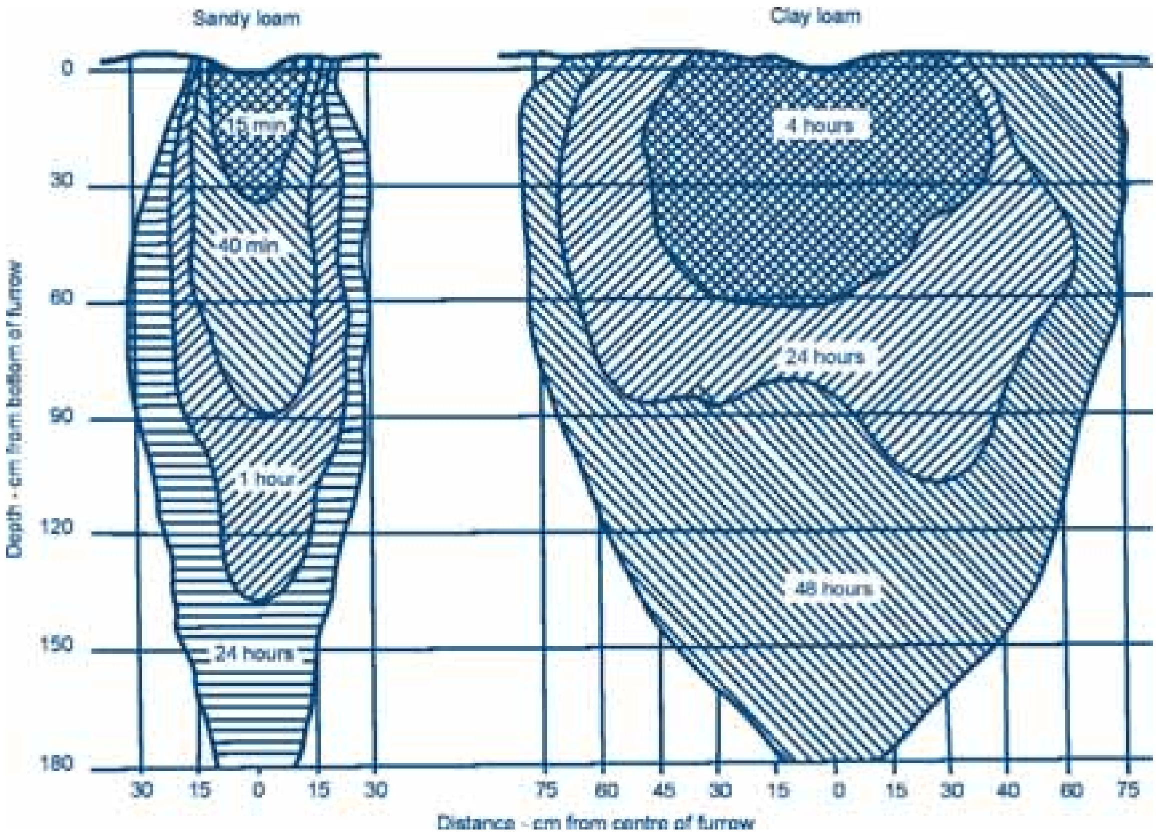


a. Deep, narrow furrow on sandy soil



b. Wide, shallow furrow on clay soil

Figure 13
Soil moisture distribution on various soil types as a determinant of furrow spacing (Source: FAO, 1985)



the stream size. Soils with low infiltration rates have usually shallow wide parabolic or U-shaped furrows to reduce water velocity and to obtain a large wetted perimeter to encourage infiltration. Sandy soils, on the other hand, require more or less V-shaped furrows to reduce the wetted perimeter through which water infiltrates (Figure 12).

Shallow furrows are suited to fields that are graded to uniform slope. The furrows should have uniform depth and shape along the whole length to prevent overtopping. The furrow should be large enough to carry the stream flow and, in general, the larger the stream size the larger the furrow must be to carry the desired flow.

Shallow-rooted crops require shallow furrows. Young crops with shallow rooting depth should be wetted with shallow furrows such that mainly the ridge is wetted. The furrow can be deepened with increased crop growth.

2.1.2. Furrow spacing

The spacing between furrows depends on the water movement in the soil, which is texture related, on the crop agronomic requirements as well as on the type of equipment used in the construction of furrows. In practice a compromise often has to be reached between these factors.

When water is applied to a furrow, it moves vertically under the influence of gravity and laterally by capillarity. Clay soils have more lateral movement of water than sandy soils because of their small pores, which favour capillary action (Figure 13). In this regard, larger spacing can be used in heavier soils than in light soils.

In general, a spacing of 0.3 m and 0.6 m has been proposed for coarse soils and fine soils respectively. For heavy clay soils up to 1.2 m has been recommended.

It should also be realized that each crop has its own optimum spacing and the ridges should be spaced according to the agronomic recommendations. In addition, the equipment available on the farm determines the furrow spacing, as this is adjustable only within limits. However, in all instances the furrow spacing adopted should ensure a lateral spread of water between adjacent furrows that will adequately wet the entire root zone of the plants.

When water and labour are scarce, or when large areas must be irrigated quickly, alternate furrows may be irrigated. In this case, the lateral spread of water is only partial, and crop yields may be reduced. An economic analysis should be carried out to determine whether the advantages of this practice outweigh any possible limitations on yield.

2.1.3. Furrow length

Under mechanized agriculture, furrows should preferably be as long as possible in order to reduce labour requirements and system costs. However, they also should be short enough to retain a reasonable application efficiency and uniformity. Application efficiency and uniformity normally increase as the furrow length decreases. Thus, when labour is not a constraint or inexpensive and/or the water supply is limited, short furrows may be most suitable. This does increase the number of field canals and overall cost of the system. For proper design of the furrow length, the following factors have to be taken into account:

- Soil type
- Stream size
- Irrigation depth
- Slope
- Field size and shape
- Cultivation practices

Soil type

Furrow lengths should be shorter in sandy soils than in clayish soils, since water infiltrates faster into light soils than into heavy soils. If furrow lengths are too long in sandy soils, too much water will be lost as deep percolation at the top end of the furrow. On heavier soils, water infiltrates slowly and therefore furrows should be longer to allow sufficient time for the water to infiltrate the soil to the desired depth. In Eastern and Southern Africa designers are often confronted with the fact that smallholders occupy land with high soil variability, both vertically and horizontally, necessitating field tests to establish the appropriate furrow length.

Stream size

On similar soils, and of the same slope and irrigation depth, furrows can be longer when a larger stream size is used for irrigation. This is because water will be advancing rapidly down the furrow. However, the stream size should not exceed the maximum non-erosive stream size determined in field trials. The following equation provides guidance in selecting stream sizes for field trials.

Equation 1

$$Q_{max} = \frac{K}{S_o}$$

Where:

Q_{max}	=	Maximum non-erosive stream size (l/min)
S_o	=	Furrow slope in the direction of flow (%)
K	=	Unit constant (= 40)

Furrow stream sizes are sometimes selected on the basis of the one-quarter rule. This rule states that the time required for water to advance through a furrow till the end should be one quarter of the total irrigation time (contact time). However, it should be noted that only field experience will show when to actually close the inflow, because of all the different factors involved (see Section 1.3.3).

Irrigation depth

A larger irrigation depth requires more contact time for water to infiltrate to the desired depth than a shallow irrigation depth, as explained in Chapter 1. The irrigation depth can be increased by making the furrow longer in order to allow more time for the water to reach the end of furrow, which increases the contact time. Care should be taken, however, to avoid too high percolation losses at the top end.

Slope

Furrows should be put on proper gradients that allow water to flow along them and at the same time allow some water to infiltrate into the soil. Furrows put on steeper slopes can be longer because water moves more rapidly. However, with slopes steeper than 0.5% (0.5 m drop per 100 m length), the stream sizes should normally be reduced to avoid erosion, thus shorter furrows have to be used. Under smallholder conditions the maximum slope of 0.5% should not be exceeded (James, 1988).

Field size and shape

Field size and shape provides challenges to designers. For the system to operate at the level of efficiency earmarked by the designer, the field shape of each farmer's plot should be regular and the length of run uniform for all farmers. This would facilitate uniform water delivery throughout the field and scheme. It is therefore advisable that for new developments this principle be adhered to and discussed in detail with the farmers during the planning consultations. Unfortunately, in practice in most cases no or insufficient effort is made to discuss this matter with smallholders.

Where an area had been cultivated by farmers under dryland conditions prior to the installation of the irrigation scheme, farmers are often even more reluctant to change the shape and borders of their individual fields. As a result the original, irregular shapes of the fields are maintained and variable lengths of run are used. This results in a complex operation of the system and water shortages, and at the same time water is wasted, leading to low irrigation efficiencies and higher operation costs. For the same reason the number of field canals increases, resulting in high development costs. This shows the importance of involving farmers from the planning stage onwards, so that they themselves also will become convinced of the advantages and necessity of regular shaped fields of equal size and thus are willing to change the original borders of their individual fields.

Cultivation practices

When cultivation practices are mechanized, furrows should be made as long as possible to facilitate working with machinery. Short furrows also require a lot of labour, as the flow must be changed frequently from one furrow to the next.

Guidelines for the determination of furrow lengths

Table 7 summarizes the main factors affecting the furrow length and the suggested practical allowable furrow lengths according to Kay (1986). The data given in this table are appropriate for large-scale and fully mechanized conditions.

Table 7

Furrow lengths in metres as related to soil type, slope, stream size and irrigation depth (Source: Kay, 1986)

	Soil type	Clay		Loam			Sand		
		Average irrigation depth (mm)							
Furrow slope %`	Maximum stream size (l/sec)	75	150	50	100	150	50	75	100
0.05	3.0	300	400	120	270	400	60	90	150
0.10	3.0	340	440	180	340	440	90	120	190
0.20	2.5	370	470	220	370	470	120	190	250
0.30	2.0	400	500	280	400	500	150	220	280
0.50	1.2	400	500	280	370	470	120	190	250
1.00	0.6	280	400	250	300	370	90	150	220
1.50	0.5	250	340	220	280	340	80	120	190
2.00	0.3	220	270	180	250	300	60	90	150

Table 8

Practical values of maximum furrow lengths in metres depending on soil type, slope, stream size and irrigation depth for small-scale irrigation (Source: FAO, 1988)

	Soil type	Clay		Loam		Sand	
		Net irrigation requirements (mm)					
Furrow slope %`	Maximum stream size per furrow (l/sec)	50	75	50	75	50	75
0.0	3.0	100	150	60	90	30	45
0.1	3.0	120	170	90	125	45	60
0.2	2.5	130	180	110	150	60	95
0.3	2.0	150	200	130	170	75	110
0.5	1.2	150	200	130	170	75	110

Table 8 provides more realistic data for smallholder irrigation.

The soil variability in most smallholders' schemes, combined with the small size of holdings, makes the scheme more manageable when shorter furrows are used. The figures in both tables should only be used as a guide in situations where it is not possible to carry out field tests. As much as practically possible, the furrow lengths should be determined in the field based on the tests described in Chapter 1.

2.2. Borderstrip irrigation

Borderstrips are strips of land with a downward slope but are as horizontal as possible in cross-section (Figures 14 and 15). A horizontal cross-section facilitates an even rate of water advance down the longitudinal slope. Borderstrips can vary from 3-30 m in width and from 60-800 m in length. They are separated by parallel dykes or border ridges (levées).

Normally water is let onto the borderstrip from the canal through intakes, which can be constructed with gates on the wall of the canal or, when unlined canals are used, by temporarily making an opening in the canal wall. The latter is not recommended since it weakens the walls of the canal, leading to easy breakage. Other means used for the same purpose is the insertion of short PVC pipes into the canal through the wall. The short pipes are usually equipped with an end cup, which is removed when irrigation is practiced. Some farmers use cloth or plastic sheet to close and open the pipe. The most appropriate method of supplying water from the canal to the field, however, is the use of siphons.

Figure 14

Example of a borderstrip irrigation system (Source: Kay, 1986)

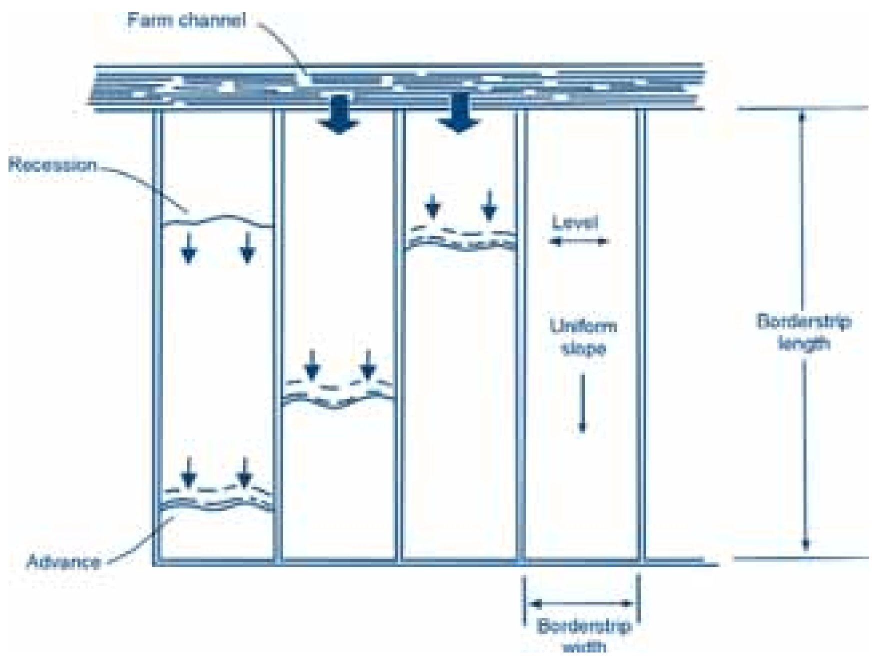
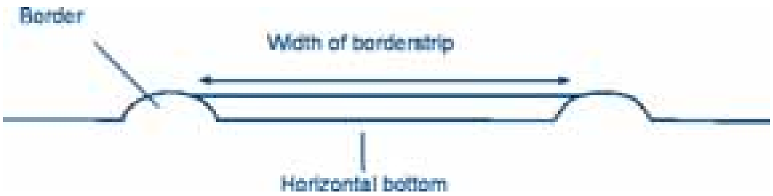


Figure 15
Cross-section of a borderstrip



Leakage should be expected from all other techniques and, as a consequence, waterlogging at the beginning of the borderstrips. The use of siphons instead of one water inlet also has the advantage that they can be spread over the width of the borderstrip, thus facilitating an equal spread of the water across the borderstrip width and then down the slope towards the lower end. To ensure a proper lateral spread, it is recommended that, longitudinally, the borderstrips be horizontal for the first 10 m or so, with a uniform downward slope thereafter. This irrigation method is particularly suitable for pasture and close-growing crops like wheat.

2.2.1. Borderstrip width

The borderstrip width depends on the topography of the field, which determines the possible width that can be obtained while keeping a horizontal cross-section without requiring too much soil movement, and on the stream size. The stream size also restricts strip width, as it should be sufficient to allow complete lateral spreading throughout the borderstrip width and length. The strip width also depends on the cultivation practices, mechanized or non-mechanized for example. Borderstrips should not be wider than 9 m on 1% cross-slopes (James, 1988).

2.2.2. Longitudinal slope of the borderstrip

The slope should, wherever possible, be adapted to the natural topography in order to reduce the need for land grading, which may lead to the removal of too much topsoil. On the one hand, slopes on sandy soils should be greater than on heavy soils to avoid deep percolation losses at the top of the field. Furthermore, the maximum slope depends on the risk of soil erosion, which is greater in sandy soils than in clayish soils. Crop cover can be a factor that counts in determining the borderstrip slope. For example, where the borderstrip will be covered by a permanent crop, such as pasture, slopes can be up to 7% for clay soils with stable aggregates (James 1988).

Borderstrips should have a minimum slope of 0.05-0.1% to allow water to flow downstream over it. The maximum slope on sandy soils ranges from 0.3-1% in humid areas and 1-2% in arid areas on bare soils and soils with good crop cover respectively. For clay soils the slope ranges from 0.5-2% in humid areas and 2-5% in arid areas on bare soils and soils with crop cover respectively (see also Module 1).

2.2.3. Borderstrip length

To determine the borderstrip length, the following factors need to be considered:

- ❖ Soil type
- ❖ Stream size
- ❖ Irrigation depth
- ❖ Land slope
- ❖ Field size and shape
- ❖ Cultivation practices

Soil type

The borderstrip length can be longer on heavy soil than on light soil because water infiltrates heavy soil more slowly. If a border is made too long on a light soil, too much water will infiltrate the soil at the top part, leading to too much water loss due to deep percolation.

Stream size

When a larger stream size is available, borderstrips can be longer on the same soils, because water will spread more rapidly across the soil surface. As a rule of thumb, the stream size must be large enough to adequately spread water across the width of border. However, it should not exceed the maximum non-erosive stream size. The design of the stream size must also result in rates of advance and recession that are essentially equal (see Section 1.3.4).

Irrigation depth

A larger irrigation depth requires more contact time for water to infiltrate to the desired depth than does a shallow irrigation depth, as explained in Chapter 1. The irrigation depth can be increased by making the borderstrip longer in order to allow more time for the water to reach the end of borderstrip, which increases the contact time. However, soil type is a limiting factor.

Slope

Borderstrips should be put on proper gradients that allow water to flow downstream over the surface yet at the same time to allow some water to infiltrate the soil. The borderstrip can be longer on steeper slopes, since water moves more rapidly. However, precautions should be taken against erosion.

Field size and shape

Existing field size and shape are often practical limits to the size of borders. However, the same remarks as mentioned under furrow irrigation (see Section 2.1.3) are valid for borderstrip irrigation.

Cultivation practices

Because borders are normally long so as to achieve good water distribution, they are very suitable for mechanized farming. The width should preferably be a multiple of the farm machinery used.

2.2.4. Guidelines for the determination of borderstrip width and length

Table 9 provides some typical borderstrip widths and lengths for various soil types, slopes, irrigation depths and flows. It should be noted that in practice borderstrip lengths are often shorter because of poor levelling. Sometimes they have to be reduced after construction, if the irrigation efficiencies turn out to be too low. It should be noted that the figures for width and length in Table 9 apply to highly-mechanized agriculture on properly levelled lands under good water management.

The figures in Table 9 may not apply to small-scale irrigators on small landholdings. Table 10 provides some guidelines for determining borderstrip dimensions felt suitable for smallholder irrigation in communal areas, where farmers are responsible for the operation and maintenance of these schemes.

Table 9

Typical borderstrip dimensions in metres as related to soil type, slope, irrigation depth and stream size (Source: Withers and Vipond, 1974)

Soil Type	Slope (%)	Depth applied (mm)	Flow (l/sec)	Strip width (m)	Strip length (m)
Coarse	0.25	50	240	15	150
		100	210	15	250
		150	180	15	400
	1.00	50	80	12	100
		100	70	12	150
		150	70	12	250
	2.00	50	35	10	60
		100	30	10	100
		150	30	10	200
Medium	0.25	50	210	15	250
		100	180	15	400
		150	100	15	400
	1.00	50	70	12	150
		100	70	12	300
		150	70	12	400
	2.00	50	30	10	100
		100	30	10	200
		150	30	10	300
Fine	0.25	50	120	15	400
		100	70	15	400
		150	40	15	400
	1.00	50	70	12	400
		100	35	12	400
		150	20	12	400
	2.00	50	30	10	320
		100	30	10	400
		150	20	10	400

Table 10

Suggested maximum borderstrip widths and lengths for smallholder irrigation schemes

Soil type	Borderstrip slope (%)	Unit flow per metre width* (l/sec)	Borderstrip width (m)	Borderstrip length (m)
Sand (Infiltration rate greater than 25 mm/h)	0.2-0.4 0.4-0.6 0.6-1.0	10-15 8-10 5-8	12-30 9-12 6-9	60-90 80-90 75
Loam (Infiltration rate of 10 to 25 mm/h)	0.2-0.4 0.4-0.6 0.6-1.0	5-7 4.6 2-4	12-30 9-12 6	90-250 90-180 90
Clay (Infiltration rate less than 10 mm/h)	0.2-0.4 0.4-0.6 0.6-1.0	3-4 2-3 1-2	12-30 6-12 6	180-300 90-180 90

* *The flow is given per metre width of the border. The total flow into a border is equal to the unit flow multiplied by the border width (in metres)*

However, in reality it seems that the widths of the borderstrips in smallholder schemes are still less than the figures given in Table 10. As an example, a typical borderstrip in a smallholder irrigation scheme in Zimbabwe can have a width varying between 2-4 m, which is even less than half of the smallest width given in Table 10.

As much as practically possible, borderstrip lengths should be determined in the field based on the tests described in Chapter 1. However, the method is best suited to projects at the planning stage. For projects that have passed through this stage, and where the length and slope of the borderstrip have been fixed by field shape and land topography during the planning stage rather than by testing, a high uniformity of water distribution can only be achieved by adjusting the stream size and the time to stop inflow, on the condition that the stream size is non-erosive. Such an arrangement, however, makes the operation of the scheme very complex for management by smallholders with limited or no past experience with surface irrigation.

2.3. Basin irrigation

A basin is a horizontal area of land surrounded by earthen bunds and totally flooded during irrigation. Basin irrigation is the most common type of surface irrigation. It is particularly used in rice cultivation, where the fields are submerged, but it is equally suitable for other crops like cereals, fruit trees and pastures – as long as waterlogging conditions do not last for too long. Ideally, the waterlogging should not last longer than 24-48 hours. It is also used for the leaching of salts by deep percolation in the reclamation of saline soils. A basin irrigation system layout is illustrated in Figure 16.

Flooding should be done using a large stream size that advances quickly in order for water to spread rapidly over the basin. The advance time should not exceed a quarter of the contact time, so as to reduce difference in contact time on the different sections of the basin. It may be used on a wide variety of soil textures, though fine-textured soils are preferred. As the area near the water inlet is always longer in contact with the water, there will be some percolation losses, assuming the entire root zone depth is filled at the bottom of the field. Coarse sands are not generally recommended for basin irrigation as high percolation losses are expected at the areas close to water intake.

2.3.1. Basin size

The size of basin is critical in the design of this irrigation method and, as for furrow and borderstrip irrigation, depends on the following factors:

- ❖ Soil type
- ❖ Stream size
- ❖ Irrigation depth
- ❖ Field size and shape
- ❖ Land slope
- ❖ Farming practices

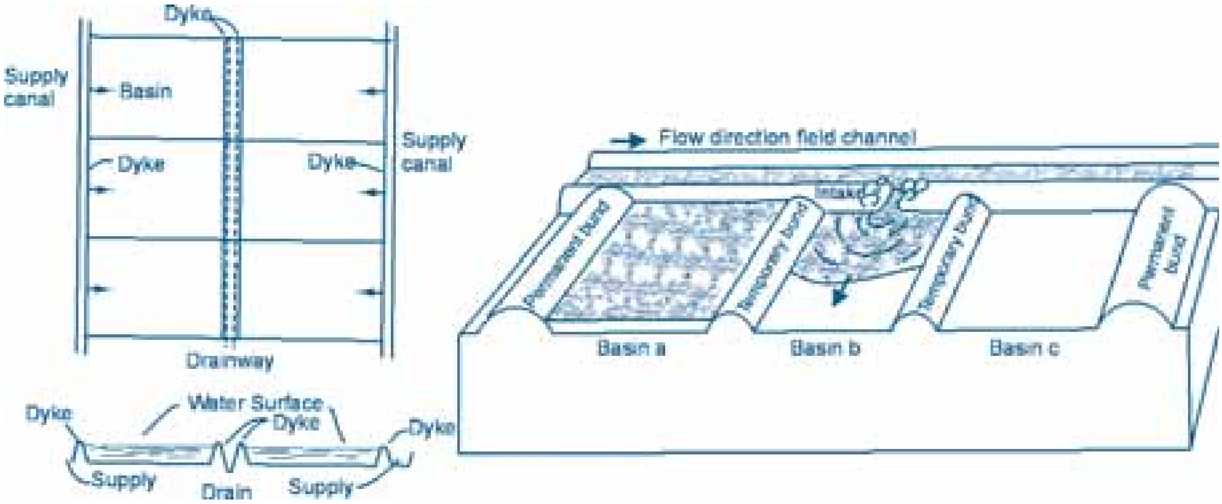
Table 11 shows in summary the general criteria for selecting a basin size, all of which will be discussed more in detail below.

Table 11

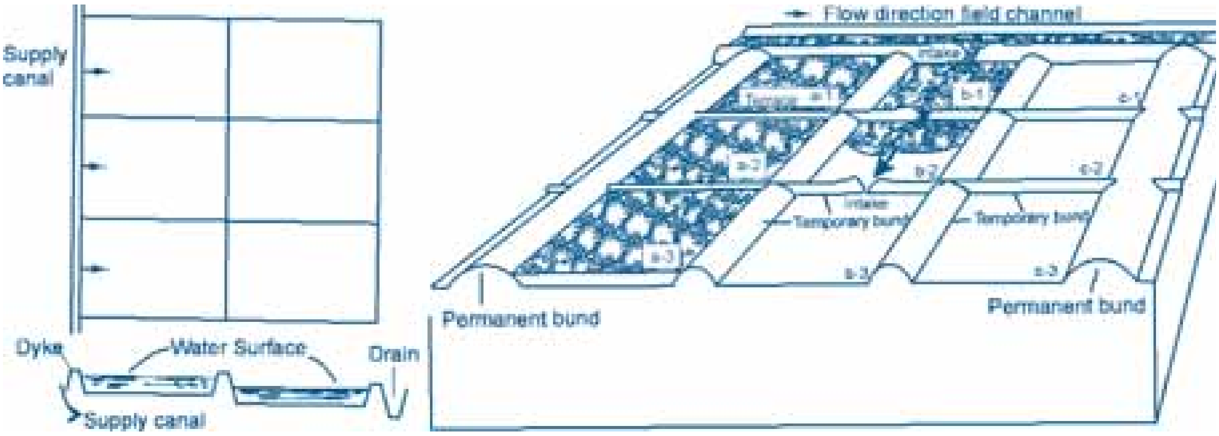
Criteria for basin size determination

Criteria	Basin size small	Basin size large
Soil type	Sandy	Clay
Stream size	Small	Large
Irrigation depth	Small	Large
Land slope	Steep	Gentle or flat
Field preparation	Hand or animal traction	Mechanized

Figure 16
Layout of basin irrigation (Source: FAO, 1985)



Direct method of water supply to the basins with a drainway midway between supply canals. “Basin a” is irrigated, then “Basin b”, and so on.



Cascade method of water supply to the basins with a tier arrangement. Ideal on terraced land, where water is supplied to the highest terrace, and then allowed to flow to a lower terrance and so on.

Soil type

Water infiltrates heavier soils more slowly than lighter soils. This means that there is more time for water to spread over the soil surface on heavy soils than on light soils before infiltrating. Therefore basins can be larger on heavier soils than on lighter soils.

Stream size

Basin size can increase with larger stream size, because water will spread more rapidly over the basin. Table 12 below gives some guidelines on basin sizes in relation to stream size and soil type.

Table 12
Basin area in m² for different stream sizes and soil types (Withers and Vipond, 1974)

Stream size (l/sec)	Sand	Sandy loam	Clay loam	Clay
5	35	100	200	350
10	65	200	400	650
15	100	300	600	1 000
30	200	600	1 200	2 000
60	400	1 200	2 400	4 000
90	600	1 800	3 600	6 000

Irrigation depth

A deeper irrigation depth requires more contact time for water to infiltrate to the desired depth than does a shallow irrigation depth, as explained in Chapter 1. The irrigation depth can be increased by increasing the size of the basin in order to allow more time for the water to reach the end of basin. This increases the contact time. However, soil type is a limiting factor. If the soil is too light then too much water will infiltrate and be lost by deep percolation next to the water inlet and too little will infiltrate furthest away from the water inlet, hence the unsuitability of basins for very light soils. It would be better to wet the whole basin as soon as possible and to leave the water ponding until the desired volume of water has been applied.

Land slope

The soil surface within each basin should be horizontal. Basins can be as large as the stream size and soil type can allow on level land. On steep slopes, the removal of the topsoil and the associated land levelling costs may be limiting factors for the basin size. Typically, terrace width varies from about 2 m for 4% land slopes up to 150 m for 0.1 % land slopes. Table 13 below provides some guidelines on the possible width of a basin, in relation to the land slope.

Table 13
Approximate values for the maximum basin width (m)

Slope (%)	Maximum width (m)	
	Average	Range
0.2	45	35-55
0.3	37	30-45
0.4	32	25-40
0.5	28	20-35
0.6	25	20-30
0.8	22	15-30
1.0	20	15-25
1.2	17	10-20
1.5	13	10-20
2.0	10	5-15
3.0	7	5-10
4.0	5	3-8

Field size and shape

Basins are best adapted to regular field shapes (square or rectangular). Irregular field shapes necessitate adapting basins. This may lead to basin sizes being different from what would be recommended based on other factors such as soil types, etc. Although a regular shape is favourable, basins can be shaped to follow contours. These are contour basins or terraces, which are seen mainly on steep slopes used for rice.

Cultivation practices

Mechanized farming requires relatively large basins in order to allow machines to turn round easily and to have long runs without too many turns. In this case, the dimensions of basins should be a multiple of the machine width. On small farms, in general 1-2 ha or less in developing countries, farming operations are done by hand or animal power. Small basins are used on such lands. The basins are often levelled by hand.

The types of crops grown may also influence the size of basins. For example, small basins could be used per single tree for orchards.

2.4. Efficiencies of surface irrigation systems and of the different surface irrigation methods

Surface irrigation schemes are designed and operated to satisfy the irrigation water requirements of each field while controlling deep percolation, runoff, evaporation and operational losses. The performance of the system is determined by the efficiency with which water is conveyed to the scheme from the headworks, distributed within the scheme and applied to the field, and by the adequacy and uniformity of application in each field (see also Module 1).

2.4.1. The different types of efficiencies in an irrigation scheme

Conveyance efficiency (E_c)

Conveyance efficiency is the ratio of water received at the inlet to a block of fields or a night storage reservoir to the water released from the project headworks. Factors affecting this efficiency include canal lining, evaporation of water from the canal, technical and managerial facilities of water control, etc. Conveyance efficiency is higher when water is conveyed in a closed conduit than when it is conveyed in an open one, since water in the latter is very much exposed to evaporation as well as to ‘poaching’ by people and to livestock watering.

Field canal efficiency (E_b)

This is the ratio of water received at the field inlet to the water received at the inlet to a block of fields or a night storage reservoir. Among other factors, this efficiency is affected by the types of lining in respect to seepage losses, by the length of canals and by water management. Piped systems have higher field canal efficiencies than do open canal systems for reasons explained earlier.

Field application efficiency (E_a)

This is the ratio of water directly available to the crop to water received at the field inlet. It is affected, for example, by the rate of supply, infiltration rate of soil, storage capacity of the root zone, land levelling, etc. For furrow and borderstrip irrigation, water is mostly lost through deep percolation at the head end and through runoff at the tail end, while for basin irrigation it is mostly through deep percolation and evaporation, since the basin is closed.

Distribution system efficiency (E_d)

Conveyance efficiency E_c and field canal efficiency E_b are sometimes combined and called distribution system efficiency E_d, expressed as:

Equation 2

$$E_d = E_c \times E_f$$

Farm irrigation efficiency (E_f)

Field canal efficiency E_b and field application efficiency E_a are sometimes combined and called farm irrigation efficiency E_f, expressed as:

Equation 3

$$E_f = E_b \times E_a$$

Overall irrigation efficiency (E_p)

The overall or project irrigation efficiency of an irrigation scheme is the ratio of water made available to the crop to that released at the headwork. It is the product of three efficiencies, namely conveyance efficiency (E_c), field canal efficiency (E_b) and field application efficiency (E_a), and is expressed as:

Equation 4

$$E_p = E_c \times E_b \times E_a \quad \text{or:}$$
$$E_p = E_d \times E_a \quad \text{or:}$$
$$E_p = E_c \times E_f$$

The field application efficiency (E_a) is the one that contributes most to the overall irrigation efficiency and is quite specific to the irrigation method, as discussed below. Any efforts that are made to improve on this efficiency will impact heavily on the overall efficiency.

2.4.2. Efficiencies of the different surface irrigation methods

Furrow irrigation could reach a field application efficiency of 65% when it is properly designed, constructed and managed. The value ranges from 50-70%. Losses will occur through deep percolation at the top end of the field and runoff at the bottom end. Properly designed and managed borderstrips can reach a field application efficiency of up to 75%, although a more common figure is 60%. With basin irrigation it is possible to achieve field application efficiencies of 80% on properly designed and managed basins, although a more common figure used for planning varies between 60-65%. For more details on efficiencies the reader is referred to Module 1.

Example 3

At Nabusenga surface irrigation schemes, it is assumed that E_c and E_b both are 90% for concrete-lined canals continuous flow and that E_a is 50%. What is the overall irrigation efficiency?

$E_p = E_c \times E_b \times E_a = 0.90 \times 0.90 \times 0.50 = 0.41$ or 41%

In order to show the importance of contribution of E_a to the overall irrigation efficiency while keeping the same E_c and E_b but increasing the field application efficiency E_a from 50% to 70%, an overall irrigation efficiency of 0.57 or 57% (0.90 x 0.90 x 0.70) can be achieved instead of 41%.

There are common problems that can reduce the field application efficiency of the three surface irrigation methods to a considerable extent. The most common ones are discussed below:

- Poor land levelling can lead to waterlogging in some places and inadequate water application in others. If the cross slope is not horizontal for borderstrip irrigation, water will flow to the lowest side causing over-irrigation in that area.
- Different soil types along the furrows, borderstrips and basins result in different infiltration rates.
- Too small an advance stream results in too long an advance time, leading to over-irrigation at the top end of the borderstrip and furrow. A small stream size diverted into a basin will take too long to cover the entire basin area, resulting in a contact time that is very different at the various sections of the basin.
- Too large a stream size will result in water flowing too fast down the borderstrip and furrow leading to a cut-off taking place before the root zone has been filled with water. If the flow is allowed to continue under these conditions there will be excessive runoff at the end. A large stream size, on the other hand, can be desirable for basins as this reduces the difference in contact time on the various sections of the basin.

- The use of irregular-shaped plots with variable lengths of run complicates the operation of the system, resulting in poor efficiencies.

As a rule of thumb, overall irrigation efficiencies used in Zimbabwe for design purposes are in the range of 40-50% when using concrete-lined canals and 55-65% for piped systems.

2.5. Criteria for the selection of the surface irrigation method

Though it is not possible to give specific guidelines as to which surface irrigation method to select under a given set of conditions, each option usually has advantages and disadvantages. The selection of a surface irrigation method depends mainly on soil type, crops to be irrigated, the irrigation depth, land slope, field shape, labour availability and water source. Table 14 gives some guidelines on which method would be most appropriate depending on soil type, crop rooting depth and net depth of application.

2.5.1. Soil type

All three surface irrigation methods prefer heavy soils, which have lower infiltration rates. A light soil with high infiltration rates favours deep percolation losses at the top of the fields, resulting in low field application efficiency.

2.5.2. Type of crop

Furrow irrigation is particularly suitable for irrigating row crops such as maize and vegetables. Furrows are also more suitable for shallow-rooted crops. Borderstrip irrigation can also be used for row crops or for close-growing crops that do not favour water ponding for long durations, such as wheat and alfalfa. Any crop, whether row or close-growing, that can stand a very wet soil for up to 24 hours is best grown in basins.

2.5.3. Required depth of irrigation application

If the application depth is small, furrow irrigation is the most appropriate method of irrigation. Field experience has shown that large application depths can be applied most efficiently with basin irrigation.

In general, the gross irrigation depth is much larger than the net irrigation depth for all three surface irrigation methods, due to the lower irrigation efficiencies of surface irrigation compared to pressurized systems (see Module 1). However, of the three surface irrigation methods, basin irrigation can have higher irrigation efficiency and use less water for the same crop on the same soil than the other methods as water is confined within bunds (see Section 2.4.2).

2.5.4. Land slope

In general terms, all surface irrigation methods favour flat land as steep slopes would necessitate excessive land levelling in order to avoid erosion, which is expensive and can lead to the removal of top soil.

Flat land with a slope of 0.1% or less is best suited for basin irrigation (which needs a zero slope) since it requires minimum land levelling. Borderstrip irrigation may be used on steeper land, even up to 5%, depending upon other limiting factors such as soil type. One has to be cautious with furrow irrigation on such steep slopes. This is because the flow is confined to a small channel (the furrow), which could result in erosion.

2.5.5. Field shape

In general, furrow irrigation requires regular field shapes, allowing the use of the same stream size for the same furrow lengths. However, for all three types regularly shaped fields are preferable, as explained in Sections 2.1, 2.2 and 2.3.

2.5.6. Labour availability

Basin irrigation requires less labour than the other two methods and might have to be considered if there is a critical labour shortage.

Table 14

Selection of an irrigation method based on soil type and net irrigation depth (Source: Jensen, 1983)

Soil type	Rooting depth of crop	Net irrigation depth per application (mm)	Surface irrigation method
Sand	Shallow	20-30	Short furrows
	Medium	30-40	Medium furrows, short borders
	Deep	40-50	Long furrows, medium borders, small basins
Loam	Shallow	30-40	Medium furrows, short borders
	Medium	40-50	Long furrows, medium borders, small basins
	Deep	50-60	Long borders, medium basins
Clay	Shallow	40-50	Long furrows, medium borders, small basins
	Medium	50-60	Long borders, medium basins
	Deep	60-70	Large basins