

MONICA SALGUERO  
LAZO DE LA VEGA



# SURDEV: Surface Irrigation Software





**ILRI Publication 59**

# **SURDEV: Surface Irrigation Software**

**Design, Operation, and Evaluation of Basin, Border,  
and Furrow Irrigation**

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**ALTERRA-ILRI**

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# Preface

The SURDEV computer package for surface irrigation is the result of years of co-operation between the Institute for Land and Water Management (ILWM) of the Catholic University of Leuven, Belgium, and the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. The SURDEV package consists of three software programs for surface irrigation: BASDEV for irrigation of basins; BORDEV for irrigation of borders; and FURDEV for irrigation of furrows.

These three programs are updated versions of earlier ones. BASDEV is the successor to versions 1 and 2 of BASCAD, the mathematical model for basin irrigation, which was developed at ILRI by Johannes Boonstra and Marinus Jurriëns and published as ILRI Publication 43. BORDEV and FURDEV are the updates of the BISDEV program for border irrigation and the FISDEV program for furrow irrigation, respectively. The early unpublished versions were written at ILWM by Dawit Zerihun, under Jan Feyen's guidance with Mr Boonstra and Mr Jurriëns acting as advisors.

BASDEV was upgraded at ILRI by Rob Kselik and FURDEV was upgraded at ILWM by Mr Zerihun. BORDEV was the result of their collaborative work. The upgrading of all the programs took place under the guidance of Mr Jurriëns and Mr Boonstra, with Mr Feyen as advisor. The four authors are most grateful to Mr Kselik for his painstaking transcribing of myriads of their wishes for a user-friendly and consistent interface.

Mr Jurriëns wrote the text for the SURDEV publication incorporating into it the comments from the co-authors, and input from Mr Boonstra for Chapters 5, 6 and 7, which are the user manuals for the three software programs. The authors gratefully acknowledge the help of Mr Karel Lenselink of ILRI, whose contributions during the writing of the text were very useful.

To our deep regret, Marinus (Rien) Jurriëns died on December 20th, 2000. Rien firmly believed that this publication could lead to improved design and more efficient use of irrigation systems. We sincerely hope that this book will live up to his expectations.

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## List of symbols

A	Exponent of the power function in the Kostiakov-Lewis and the modified Kostiakov-Lewis infiltration function
A	Cross-sectional area of flow
A	Field area
a	Coefficient of the power function in the SCS infiltration function
ATR	Advance time ratio
b	Exponent of the power function in the SCS infiltration function
CBR	Cutback ratio
$C_1, C_2$	Constants dependent on furrow geometry parameters
c	A constant in the SCS infiltration function
D	Depth of water
$D_a$	Applied depth
$D_{av}$	Average infiltrated depth
$D_{dp}$	Deep percolation depth
$D_i$	Cumulative infiltrated depth
$D_{max}$	Maximum infiltrated depth
$D_{min}$	Minimum infiltrated depth
$D_{over}$	Average depth of over irrigation
DPR	Deep percolation ratio
$D_{req}$	Required depth
$D_s$	Average depth stored in the crop root zone
$D_{sr}$	Amount of surface runoff expressed in terms of depth per unit area of a border or a furrow
DU	Distribution uniformity
$D_{under}$	Average depth of under irrigation
$E_a$	Application efficiency
$E_s$	Storage efficiency
$f_0$	Coefficient of the linear term of the modified Kostiakov-Lewis infiltration function
I	Infiltration rate
IF	Intake family
k	Coefficient of the Kostiakov-Lewis and the modified Kostiakov-Lewis infiltration function
L	Field length
LQDU	Low quarter distribution uniformity
$L_{over}$	Length of over-irrigation
$L_{under}$	Length of under-irrigation
N	Number of measurement stations/calculation nodes
n	Manning's roughness coefficient
n	Number of points along the length of a field
Q	Flow rate

$Q_{cb}$	Cutback flow rate
$Q_o$	Inlet flow rate
$q_o$	Unit flow rate
$q_{max}$	Maximum non-erosive flow rate
$R$	Hydraulic radius
$S_o$	Bed slope
$SRR$	Surface runoff ratio
$T$	Infiltration opportunity time
$T_a$	Advance time
$T_{co}$	Cutoff time
$T_d$	Depletion time
$TRR$	Tailwater reuse ratio
$T_r$	Recession time
$T_{i(100)}$	Infiltration opportunity time for a depth of 100 mm
$UC$	Uniformity coefficient
$v_{max}$	Maximum non-erosive velocity
$W$	Width of basin or border
$W_s$	Furrow spacing

# 1 Introduction

## 1.1 The importance of surface irrigation

Many countries depend on surface irrigation to grow crops for food and fibre. Without surface irrigation, their agricultural production would be drastically lower and problems of unreliable food supply, insufficient rural income and unemployment would be widespread. Their national economies would dwindle and put an intolerable pressure on the daily life of the people; a fact especially true of countries in the subtropics. Without surface irrigation, Egypt and Pakistan, for example, would not have any agriculture worth mentioning, and India and China would face serious problems with trying to maintain food security.

Although precise data are lacking, we estimate that surface irrigation accounts for some 80 to 90 per cent of the total 260 million hectares of irrigated land worldwide, mainly in developing countries in the tropics and subtropics, where hundreds of millions of farmers depend on surface irrigation to grow their crops. This widespread use of surface irrigation is chiefly attributable to the low capital investment involved, low operating costs and ease of operation and maintenance.

## 1.2 Expansion and negative effects

After the Second World War, the total irrigated land in the world expanded enormously. In many developing countries, large-scale surface irrigation systems became popular because they were cheaper and easier to maintain than pressurised systems. National governments and international aid agencies promoted surface irrigation so that developing countries could produce enough food crops to feed themselves, and earn foreign exchange by selling their agricultural surplus on the world market. In industrialised countries, in contrast, pressurised irrigation systems became very popular because of their low labour and land levelling requirements, and their potential for high application efficiencies.

In the nineteen eighties, however, farmers in the Western world and particularly those in the western states of the USA, began to abandon their sprinkler systems in favour of the old surface irrigation methods. They had come to realise that sprinkler systems involved high capital investments with high annual costs of operation and maintenance, and that the irrigation efficiencies they achieved were not always as high as the manufacturers claimed they would be. New developments like the surge flow technique reduced labour costs and increased control over irrigation systems. In addition, the introduc-

tion of new technologies, such as laser-controlled land levelling and automatic field water-supply systems, paved the way for efficient surface irrigation systems, provided they were properly designed and used.

Nevertheless, the general perception was that surface irrigation went hand-in-hand with low application efficiencies and that timely and even applications of water was difficult to achieve. Substantial water losses often occurred raising groundwater levels and creating drainage problems in many regions of the world. Large areas of agricultural land have been degraded and even lost because of soil waterlogging, salinity, and alkalinity. Poor surface irrigation practices resulting in low irrigation efficiencies and uniformities have led to reduced crop yields. In areas where water is in short supply, farmers struggle with each other for water and inequitable water distribution is prevalent. As water shortages become more acute worldwide, there is a growing need for "vertical" expansion, ie, increasing yield per ha in existing irrigation schemes, rather than "horizontal" expansion, ie, creating new irrigated areas. To increase agricultural production, it will be necessary to increase irrigation efficiencies on farm fields.

### 1.3 Basic principles

Surface irrigation relies on gravity to spread water over the farmers' fields. Following the pull of gravity, the water flows over the fields from one end to the other, infiltrating into the soil as it goes. The most common surface irrigation techniques are level basins (with or without level furrows), sloping borders and sloping furrows to distribute irrigation water. The purpose of all of these techniques is to supply water in the right quantity, at the right time and in an even layer, to achieve a uniform crop stand and minimise water losses. Success of the techniques depends on proper design and operation of surface irrigation systems at field level, to help farmers achieve good crop yields, use precious water resources more efficiently and limit waterlogging and salinisation of the soil.

Surface (or gravity) irrigation systems are one of the three major categories of irrigation systems, the other two being subsurface irrigation systems and pressurised irrigation systems. Pressurised systems include drip or trickle irrigation and a wide variety of sprinkler systems, all of them based on using pressure to deliver water to where it is needed through a network of pipes. Subsurface irrigation works by controlling groundwater levels, keeping them high enough to enable crops to use groundwater from capillary rise and low enough to avoid waterlogging in the upper soil layer.

## 1.4 From mathematical models to computer programs

For decades, engineers have been developing mathematical models of the entire process of surface irrigation to improve irrigation efficiencies. The many variables of these models include field dimensions, field slope, flow rate, cutoff time, soil-infiltration characteristics, and flow resistance. Interactions between the variables determine advance time, recession time, infiltrated depths and corresponding irrigation efficiencies and uniformities. Today, there are complete hydrodynamic models, simplified zero-inertia models and upgrades of older volume balance and kinematic-wave models, all of which are simplified representations of a real-life physical system, expressed in sets of mathematical equations. Data from mathematical models have allowed engineers to systematically improve irrigation system design and operation, which, for many years were mainly based on rule of thumb, rough empirical guidelines and approximations.

Thanks to mathematical models, engineers have learned more about the processes that govern the behaviour of a given irrigation event. New theories and computer programs have gradually made it possible to do numerical simulations and compute the entire surface irrigation process with far more ease and accuracy. Mathematical models for design, operation, and evaluation of the various surface irrigation methods have been used to develop computer programs. Software for surface irrigation has followed in the wake of the rapid spread and application of personal computers. Although most of this software comes from Western USA, where irrigation practices differ significantly from those in most developing countries, it has practical applications for surface irrigation in other parts of the world too.

The present availability of good, user-friendly programs has enabled mathematical models to make the transition from the classroom and research laboratory to field use. Nonetheless, a fine mathematical model does not necessarily make a fine computer program, because a huge effort is still necessary to convert a smooth-running program into a user-friendly software tool, with an interface that is convenient for both developer but average user. Programs that are available today are practical tools that make it easy, quick, and cheap to compute irrigation scenarios and solutions to irrigation problems. The purpose of this book and accompanying software is to provide irrigation professionals with some of these tools.

## 1.5 Summary

This book is about the SURDEV computer package comprising three programs that simulate different methods of surface irrigation: BASDEV for level basins, BORDEV for borders and FURDEV for furrows.

Chapter 2 summarises the methods and principles of surface irrigation, and various computer applications for modelling, design, and evaluation of surface irrigation systems. Chapter 3 presents the variables and parameters involved in surface irrigation and directions on how to quantify them. The introduction to SURDEV begins in Chapter 4, which contains general features of this computer package, including the basic operating (interface) features common to BASDEV, BORDEV, and FURDEV. Chapters 5, 6 and 7 are the user manuals for these programs, each containing sample problems. Chapter 8 describes how to use the more advanced applications of the programs to solve and evaluate various surface irrigation problems, especially those encountered under farming conditions in developing countries.

There are two appendices that outline the theoretical principles of BASDEV, BORDEV, and FURDEV, including basic algorithms and verifications. For other—and more theoretical—details, we refer the reader to the standard literature.

This text will interest engineers, researchers, trainers, students, and teachers who want to know more about surface irrigation methods and the user-friendly software available to simulate and analyse them. BASDEV, BORDEV and FURDEV can solve many problems of surface irrigation design, operation and evaluation, and can compare the options of a single irrigation method and of several different methods. They are valuable tools for developing and testing practical guidelines for a given set of conditions.

We have taken great pains to make BASDEV, BORDEV and FURDEV user-friendly. All three are MS-DOS programs, but can be run under Windows. All three have a clear and complete interface with an extensive online HELP option. All are stand-alone programs that the user can operate without extensive reading of the manual or detailed knowledge of the numerical techniques and governing equations used in building the mathematical algorithms. To get the maximum from the programs, the user should have a basic understanding of the irrigation methods to which they refer.

## 1.6 A note of caution

The user should realise that a mathematical model, however complicated and theoretically correct it may be, is always a simplification of the real world and based on inherent assumptions, which also applies to a computer program based on such a model. BASDEV, BORDEV and FURDEV assume uniform conditions in time and space, but a good irrigation engineer knows that infiltration rates, for example, may vary considerably within a single field and between irrigations. It is therefore important to be aware of the capabilities and limitations of the programs presented here, and is the reason why we urge the user to apply BASDEV, BORDEV and FURDEV only to the situations for which they were designed.

SURDEV cannot solve all surface irrigation problems. No single computer package can do this. SURDEV will, however, give the user a better understanding of surface irrigation and the relationships between the many variables involved. This can help the user to improve and enhance the design and operation of surface irrigation systems and the judicious use of the water supply.

Finally, we must remind the reader that a computer simulation is only one-technical-facet of the surface irrigation diamond. Many more facets will need scrupulous attention before achieving the maximum effect of the design and operation of all surface irrigation systems.





## 2 Methods, principles and models

### 2.1 Methods of surface irrigation

#### 2.1.1 General

In surface irrigation, water is released from a channel directly onto a farmer's field. Drawn by the pull of gravity, the inflow advances towards the downstream end of the field, slowing down as the water infiltrates into the soil. When the inflow reaches the downstream end of the field, it either stops (if the flow path is blocked), or it leaves the field as surface runoff (if the flow channel is free-draining). When the field has received enough water the inflow is cut off, which can happen either before or after the water front reaches the end of the field. Any water remaining on the surface of the field can either infiltrate into the soil or flow away as surface runoff. If the inflow travels along sloping flow channels, it starts to disappear from the upstream end of the field while the drying front continues to travel downstream until all water has disappeared. In theory, on a level field all of the surface water disappears at the same moment in time. Part of the water that infiltrates into the soil profile may percolate beyond the root zone. Primary factors that affect the uniformity of the inflow distribution over the length of a given field are flow rate and infiltration rate. Secondary factors are flow resistance of the soil surface, field slope and geometry of the flow cross-section.

Surface irrigation is the oldest and most widespread way of providing agricultural crops with water. There are several methods of surface irrigation, the most common being level basins, borders and furrows for inflow to farmers' fields. All of these methods can be automated. All of them can be adapted for use with a wide range of soils, topographies, crops and water sources. Most farmers have developed the experience necessary for laying out and using surface irrigation systems. Structures or devices at field level are generally uncomplicated and easy to make from locally available material. Operating and maintaining basins, borders and furrows, however, can require substantial investments of time and labour. This is especially true of maintaining proper land levelling, which is necessary for achieving high irrigation efficiencies and uniformities of irrigation applications. Inadequate levelling reduces the quality of irrigation dramatically by causing local over or under-irrigation.

We describe the use of level basins, sloping border strips and sloping furrows in the subsequent sections. For more information, we refer the reader to general texts on surface irrigation.

### 2.1.2 Level basins

A level basin is a field that has been levelled and entirely banded (Figure 2.1). The bunds keep water stored on the field's surface so that it can gradually infiltrate into the soil; none of the water is lost to surface runoff. Here, we shall refer to level basins simply as basins.

Basins can be square or rectangular, but they can also have an irregular shape. Peri et al. (1979) state that a field can be considered a basin as long as the ratio of length to width is not more than about 10:1. Fields in which this ratio is higher are usually called level borders. Walker and Skogerboe (1987) reserve the term border for fields where there is surface runoff.

Basins in many countries of the tropics and subtropics are small; some as small as 100 m<sup>2</sup>! Much larger basins are feasible, provided the topography, soil type and available capital and technology allow for the required land levelling. A field with furrows or raised beds can be considered a basin as long as these are banded and level and the water can flow undisturbed from head end to tail end. A basin has no gradient, but sometimes it can have a limited slope in the direction of flow. Hart et al. (1980) state that the total "fall" of a basin should not be more than one-half the depth of the irrigation application.

Basins work best in areas where the slope is gentle and uniform and the soil intake is moderate to low. They can also work in areas where the soil intake is higher, but only if the basins are relatively small or the flow rate is high or both. Basins work well for crops that are deep-rooted and closely spaced, but not for crops that are sensitive to flooding (dry-foot crops) or crops grown on soils subject to crusting, unless the field is furrowed or raised. In areas where rainfall intensities are high, basins should have outlets to enable

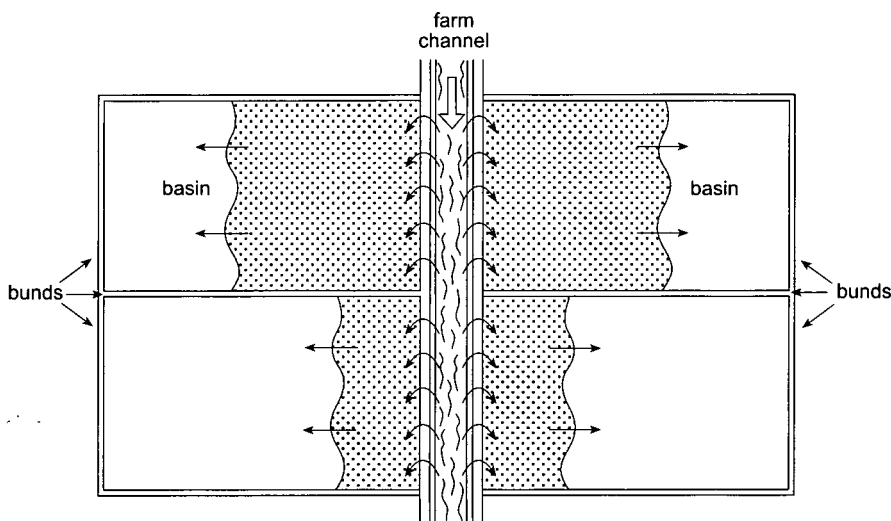


Figure 2.1 A level basin

emergency drainage of excess water. Precise land levelling is essential for good irrigation performance, especially in larger basins.

Flow size per unit width is generally high to cover the basin area as rapidly as possible, after which the flow should be cut off. Because the water levels out over the soil's surface it will disappear from the entire field almost at the same moment in time.

### 2.1.3 Border strips

Border strips are long, narrow sections of land (strips) that are bounded lengthways by parallel earthen ridges (borders). The ratio of length to width of the strips is usually greater than 10 (see Figure 2.2). The section of field between the borders is called the border strip, usually border for short, and the method of irrigation is simply called border irrigation. Graded borders slope lengthways, but they are level crosswise. They are often free-draining at the lower end. If they are dyked at the downstream end to prevent runoff, they are called check borders or dyked-end borders. The main differences between open-ended (free-draining) borders and basins are surface runoff and slope, while check borders and basins only differ in slope. There are straight borders (that run down the main, graded slope) and contour borders (that follow approximately the natural topography of the land). Here, the term border irrigation refers to irrigation of straight, rectangular and graded border strips that are open-ended.

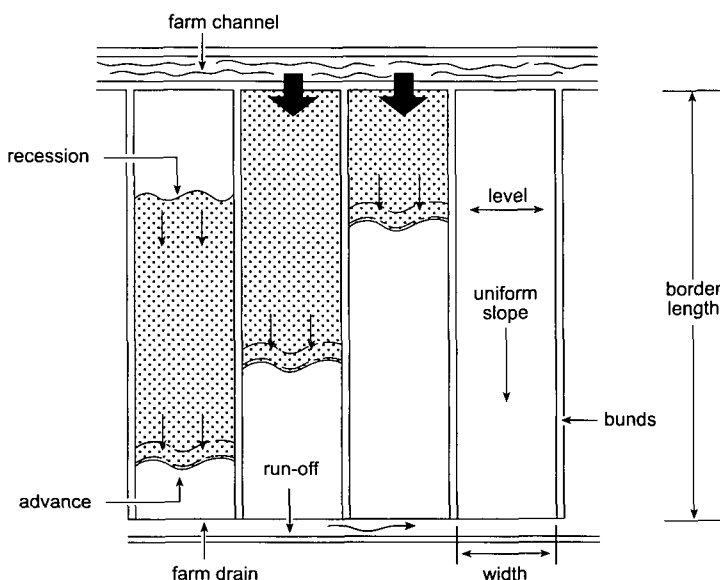


Figure 2.2 A straight, graded border

Topographic requirements for borders are less stringent than for basins. Borders are generally used on slopes of less than 0.5 per cent, but can also be used on steeper slopes if the crop and the soil are suitable (Hart et al. 1980). Borders are used on soils with moderate intake rates. The soils should not crust easily, unless the crops are grown on beds. Check borders are suitable mainly for crops grown closely-spaced, although other crops can be grown in them with the exception of rice which needs prolonged ponding.

Flow per unit width for borders must be sufficient to cover the field rapidly, although this is usually less than for basins. After inflow stops, the water disappears from the upper end to the lower end, unlike in basins where the water disappears almost all at once. To use water more efficiently, surface runoff can be pumped back and used again on another border. An alternative method is to reduce inflow before the water front has reached the border end. Precise land levelling is a prerequisite to achieving good water-application performance in borders, just as it is in basins.

#### 2.1.4 Graded furrows

Graded furrows are small parallel channels that are separated by raised beds or ridges on which the crops grow (Figure 2.3). Graded furrows are generally suitable for dry-foot, row crops. They can be laid out to approximately follow the contour of the land, or to run down the slope, or to run at a selected angle. A small cross-slope is permissible in a furrowed field.

Graded furrows can be laid out on moderate to high slopes. Land grading is less critical in furrows than in basins. Furrows can also be laid out in level fields, in which case the fields are known as furrowed basins. Furrows are

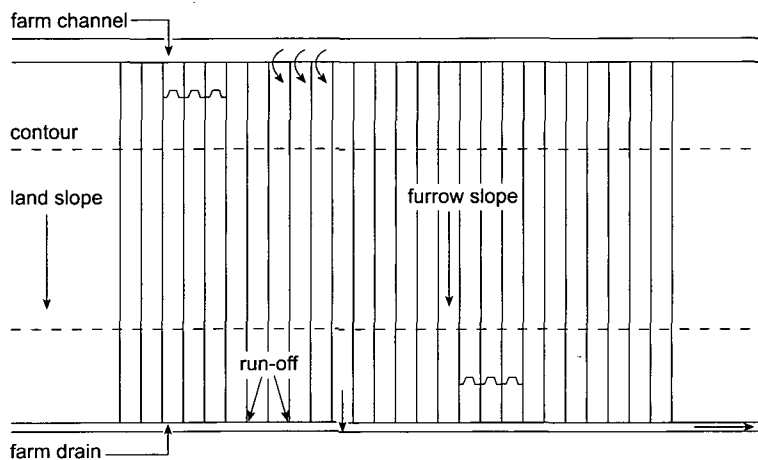


Figure 2.3 Graded furrows

often used on medium-to-heavy-textured soils. Their disadvantages are that: they are prone to high salinity in the ridges that separate them; they may be more susceptible to erosion; and the risk of high tailwater losses may be greater. They can be end-blocked to reduce these losses.

Levelling and variations in soil do not affect the uniformity of wetting in furrows much. Their small wetted area can reduce evaporation losses in widely-spaced crops. Flow rates are generally lower in furrows than in basins and borders. The total amount of flow available can easily be adjusted by varying the number of furrows that are watered simultaneously. Increasing the efficiency of free-draining furrow irrigation can be done by either using the runoff (reuse) or by reducing the inflow at the appropriate time (cutback).

An essential feature of furrow irrigation is that water initially infiltrates into the soil in all directions, not only down the length of the furrows, but also sideways into the ridges. Thus, although furrow irrigation starts off as a three-dimensional phenomenon, it is normally treated as a two-dimensional phenomenon involving horizontal surface flow and vertical infiltration only.

### 2.1.5 A comparison

Table 2.1 summarises the different features and aspects of suitability of the main methods of surface irrigation, as discussed in the previous sections. For more detailed information on determining the appropriate method for a particular situation, we refer the reader to standard irrigation textbooks and to Brouwer et al. (1989) and Finkel and Nir (1983).

Table 2.1 A comparison of the main methods of surface irrigation

	Basins	Borders	Furrows
Flow section	Wide, rectangular	Wide, rectangular	Various shapes
Infiltration	Vertical only	Vertical only	Vertical and sideways
Slope	Longitudinal slopes and cross-slopes zero or nearly zero	Slope length usually <0.5%, but can go up to 4% in sod crops; avoid cross-slopes	Slope length usually <1%, but can go up to 3%
Method of operation	Constant flow	Fixed flow, cutback, and reuse	Fixed flow, cutback, and reuse
Topography	Flat, or uniform, gentle slopes	Relatively flat, uniform slopes	Rather wide range of topographic conditions
Crops	Most crops that tolerate some inundation; narrowly-spaced crops; orchards; rice	Most dry-foot crops	Most row crops
Soils	Medium to fine textured	Moderately low to moderately high intake rates	High and low intake rates; not on soils prone to puddling

Irrigation water supply does not appear in the table. We shall discuss it in more detail later on, with emphasis on flow rates. Costs of irrigation development and construction vary primarily according to topography. They are not included in the table, nor do we discuss them further. The same goes for inlets. In terms of performance and operation, the potential of irrigations efficiencies is highest in level basins, especially the small ones, which are the easiest to operate and the least affected by injudicious operation. Furrows are often the most difficult to operate, particularly when they are long and flows are high. In terms of maintenance, larger basins require the most precise levelling. Furrows are the most labour-intensive, requiring frequent maintenance to keep their proper slope and shape.

Proper operation requires not only effort and time, but also a thorough understanding of the specific irrigation method, the feel of how to get the most out of it and experience with using it. Social preferences and local customs often govern the irrigation practices of farmers. Yet, it is important to know which flow rate to use and for how long to suit the specific physical conditions (eg, soil type, soil roughness, slope, field dimensions). Different combinations of conditions will produce different irrigation results. A farmer may be aware of these relationships, but he usually does not know to what extent they are influenced by variations in the prevailing conditions. We shall discuss these relationships and influences at length in subsequent chapters.

## 2.2 Principles of surface irrigation

### 2.2.1 Hydraulic phases

To irrigate land is to supply it with water at a certain flow rate and for a certain duration. As a rule, surface irrigation has four hydraulic phases (Figure 2.4):

1. The *advance phase*, which lasts from the start of the inflow until the time that the advancing water front reaches the downstream end of the field. The latter is known as the *advance time*. As the water advances over the soil surface some of it infiltrates into it. Infiltration causes the flow rate and flow velocity to decrease, so the closer the water front gets to the end of the field, the longer it takes to cover a unit of distance. This slowdown is reflected in the shape of the *advance curve* from which the time that it will take the water front to reach a certain point on the field can be read.
2. The *ponding phase* or *storage phase*, which lasts from the advance time until the time the inflow is stopped because sufficient water has been supplied to the field. The latter is known as the *cutoff time*. Other terms for cutoff time are "application time" and "irrigation time". During the ponding phase, the water depth on the soil surface increases and, in open-ended systems, surface runoff at the end of the field starts.

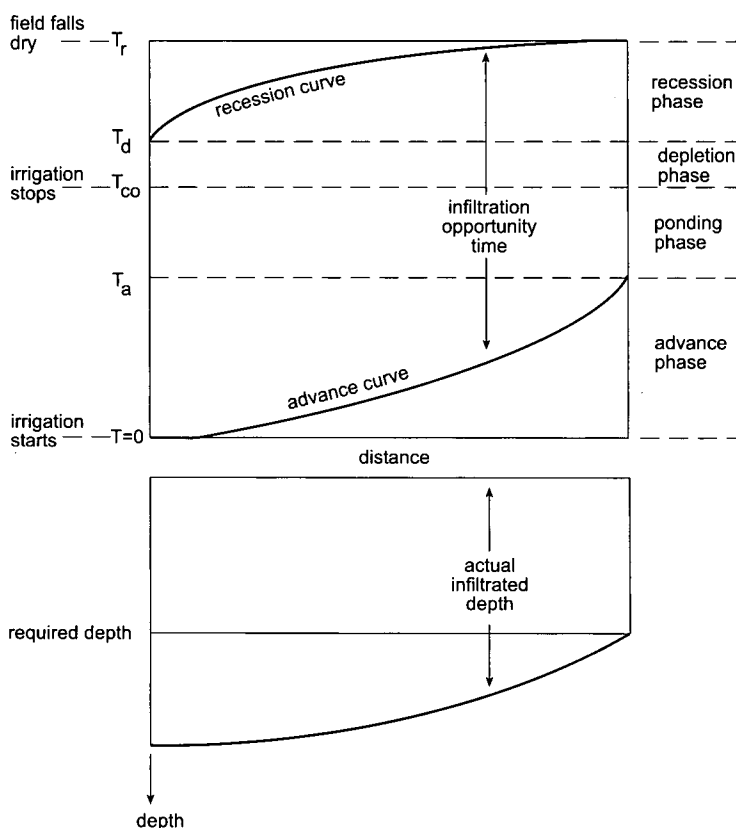


Figure 2.4 Surface irrigation process

3. The *depletion phase*, which lasts from the cutoff time until the time that the upstream end of the field falls dry. The latter is known as the *depletion time* or the *lag time*. Surface water storage decreases during the depletion phase.
4. The *recession phase*, which lasts from the depletion time until the time that the downstream end of the field falls dry. The latter is called the *recession time*. The surface water disappears gradually in a downstream direction. The *recession curve* shows when the water will disappear from the surface at every point along the length of the field.

There may be differences in the duration of phases depending on the surface irrigation method used. In level basins, for example, there is no surface runoff – and ideally – water disappears from the entire field at the same moment purely as a result of infiltration. When this happens, the depletion and recession phases coincide and the depletion (or recession) curve is horizontal. In graded borders and furrows, the depletion phase is often short because the

water level at the field inlet is fairly shallow and drops due to a combination of infiltration and continued surface flow. During the recession phase of graded borders and furrows, infiltration and surface flow causes the water front to retreat further. In open-ended systems this flow includes surface runoff at the lower end, whereas in blocked systems the water level at the far end drops by infiltration only towards the end of the recession phase.

Other differences in phase duration can occur when inflow at the upper end of the field is cut off before the water front has reached the lower end of the field. In this case the cutoff time is shorter than the advance time which means there is no clear ponding phase, so there may be an overlap between the advance phase and the depletion and/or recession phases.

### 2.2.2 Process and purpose

The surface irrigation process can be summarised as follows:

- Water is put onto the field at a certain flow rate and for a certain duration.
- Water leaving the inlet is divided between overland flow and infiltration.
- The spreading of water over the field depends on the combination of flow rate and field characteristics (eg, field dimensions, flow resistance, slope).
- The flow rate reduces down the field because water infiltrates into the soil at a rate depending on the soil infiltration characteristics.
- The shape of the advance curve is the result of the two processes of overland flow and infiltration.
- Some of the flow may or may not run off after it reaches the end of the field, depending on the surface irrigation method (basins, borders, furrows).
- The surface runoff and the infiltration together determine the shape of the recession curve.
- The difference between the advance curve and the recession curve is the infiltration opportunity time, which determines the final infiltration profile.
- The final infiltration profile and the surface runoff together determine the level of surface irrigation performance provided that it has reached the required depth at the end of the field (Figure 2.4).

The purpose of surface irrigation is to get the water to infiltrate to a certain target depth, the *required depth*, uniformly distributed over the length of the field. The time needed for the water to reach the required depth is called the “required time” or “*net opportunity time*”. The actual infiltrated depth at a certain point along the field depends on the *infiltration opportunity time*, which is the time when the water front arrives until it dries up. In Figure 2.4 we assumed that the actual infiltrated depth at the downstream end of the field equals the required depth, consequently, the net opportunity time equals the recession time minus the advance time. Therefore, to achieve infiltration to the required depth over the length of the field, designers and operators should



follow the guidelines below:

- Make the infiltration opportunity time and the net opportunity time as equal as possible to ensure infiltration to the required depth.
- Make the advance curve and the recession curve as parallel as possible to ensure equal infiltration (uniformity) over the entire length of the field.
- Minimise the runoff at the end of the field.

These guidelines can be followed fairly closely by adjusting the amount and duration of the inflow and by changing the field dimensions, assuming that other field characteristics cannot be changed. The success of the operation is usually measured in terms of adequacy, efficiency, and uniformity of the irrigation application.

### **2.2.3 Methods of operation**

So far, we have assumed that the flow rate until the cutoff time ( $T_{co}$ ) is constant. Applying a constant flow rate is a simple method of operation that requires neither extra attention from the farmer nor automatic control of the flow rate. This method can, however, make it difficult to realise good irrigation efficiency because it causes high surface runoff, particularly in open-ended borders and furrows. Somewhat more complicated methods of operation to improve irrigation efficiency are cutback, reuse, and surge flow.

#### *The cutback method*

Runoff losses from open-ended furrows and borders can be reduced either by blocking the lower ends of the furrows and borders or by reducing the inflow (cutback) at a pre-determined moment. With the cutback method, irrigation starts at a selected flow rate and continues at this rate for part of the application period. At a certain moment, the flow rate is cut back to a level that is sufficient to complete the irrigation application adequately. In furrow and border irrigation systems, it is usually assumed that this moment will come at the end of the advance phase. This is a fairly easy way to use the cutback method.

The purpose of the cutback method is to reduce surface runoff and create more uniform infiltration. Operating a surface irrigation system successfully with this method requires either more involvement of the farmer or automatic control of the inflow, plus a thorough understanding of when and how much to cut back the flow rate. A drawback is that the cutback method is practical only when the remaining flow is used to irrigate other furrows and borders.

#### *The tailwater reuse method*

The tailwater reuse (or recovery) method can be used only in open-ended borders and furrows. Closed surface irrigation systems do not have surface

runoff, and so there is no tailwater to use for an extra irrigation application. The reuse method, like the cutback method, aims to reduce total runoff losses. Surface runoff can either be collected in a ditch or sump and then pumped back to the head end of the same field, or it can be used to irrigate borders and furrows downstream. If you intend to pump water back onto the same field, you should realise that considerable extra costs for the necessary equipment to do this will be incurred.

#### *The surge flow method*

The surge flow method can be used if inflow at the head of the field is regulated automatically, eg, through gated pipes (Walker and Skogerboe 1987). With the surge flow method, you do not initiate cutback by reducing the flow size at a certain moment, but rather by closing and opening the valves in the gated supply pipes several times in succession. The advantage of this method is that if you carefully assess the required application depth and then time the surges of inflow accordingly, a higher irrigation efficiency can often be achieved. One reason for this seems to be the formation of a surface seal during the first cycle of surge and cutback, which reduces the infiltration rate and allows the irrigation water front to advance toward the end of the field more quickly. The surge flow method requires computer modelling or extensive field experience to achieve optimum inflow rates and cycle times. This method is not widely used because it is fairly complex and automatic regulation of the inflow system is costly.

## **2.3 Computer applications in surface irrigation**

### **2.3.1 Mathematical modelling**

The many variables and interactions involved in surface irrigation make it a complex process that is difficult to simulate quantitatively. For years the only design aids for irrigation engineers were tables and simple formulae, which gave only very rough guidelines. These appeared in a manual by Booher (1974) and – in a different or condensed form – in handbooks by Jensen (1980), Kay (1986), James (1988) and Cuenca (1989). The most prominent and most widely used manuals during the 1970s and 1980s were those published by the United States Department of Agriculture, in particular the manuals on basins and borders (USDA 1974), followed by the manual on furrows (USDA 1983). These included many formulae and diagrams that were the accepted design standard in the United States for a number of years.

This all changed with the advances in computer programming in the 1970s and the spread of personal computers in the 1980s. Mathematical modelling of surface irrigation became more sophisticated, giving a more complete picture of the processes involved. So, irrigation engineers started making com-

puter programs of mathematical models that a wide variety of users could apply without practical problems. As computer programs become more widely available the previous approaches will become outdated. Indeed, some of them have already lost their practical relevance.

The many mathematical models that have been developed to date fall into four major categories: fully hydrodynamic, zero-inertia, kinematic wave and volume balance models. A fully hydrodynamic model is the most complex and the most accurate. It is based on the complete Saint-Venant equations for conservation of mass and momentum. A zero-inertia model is a slightly simplified version of the complete Saint-Venant equations that leaves out the acceleration or inertia terms in the momentum equation. A kinematic wave model uses further simplifications and uniform flow assumptions. The simplest model, ie, one that involves the largest number of assumptions, is a volume balance model. It is based on the analytical or numerical solution of temporally and spatially-lumped mass conservation, commonly referred to as the "volume balance approach". This approach has become more refined over time, both conceptually and numerically.

### **2.3.2 Computer programs**

The literature contains information on many mathematical models for surface irrigation, but very few of these have led to workable, user-friendly computer programs. Those that have and are currently available are presented below. Considering how long it has taken most of them to reach their present stage of development, we do not expect them to become obsolete soon. The exception is BRDRFLW (Strelkoff 1985) which has already been superseded by newer surface irrigation programs. We mention it here because it was the first program to simulate border and basin irrigation, and it has influenced the development of subsequent programs. It was based on the zero-inertia model. Later versions included an option to use the kinematic-wave model. However, because of rapid advances in computer programming BRDRFLW was never fully developed for wider practical use, and was ultimately replaced by SRFR, early versions of which were informally distributed until its publication in 1990 (Strelkoff 1990). A new version of SRFR has recently been issued (USWCL 1999). It gives the user the choice of several calculation options.

At approximately the same time that Strelkoff was developing BRDRFLW, Boonstra and Jurriëns were developing BASCAD (the forerunner of BASDEV). BASCAD offered the user the choice between the various design and operation options for level basin irrigation. It combined a variant of the Eulerian control-volume approach (Walker and Skogerboe 1987) and a modified zero-inertia approach to model the advance phase. While the authors were developing BASCAD, they frequently tested and compared the results with those from informal versions of BRDRFLW. Their results were practically

identical to those of the zero-inertia model. It was published as ILRI Publication 43 in 1988.

Using the BASCAD concept, the Institute for Land and Water Management (ILWM) of the Catholic University of Leuven, Belgium, developed surface irrigation programs for borders and sloping furrows. BISDEV (the forerunner of BORDEV) and FISDEV (the forerunner of FURDEV) were based on the volume balance model, which uses the approach and techniques described by Walker and Skogerboe (1987); both programs were only informally distributed. While BASCAD was nearing completion at ILRI, the United States Water Conservation Laboratory in Phoenix was busy developing a new program for basin irrigation called BASIN. The final version (Clemmens et al. 1995), which differs considerably from earlier ones, is based on graphs that the authors prepared using the dimensionless solution approach of the zero-inertia model. BASIN allows the user to choose from various design and evaluation options, including maximum length and operational advance ratios.

Two surface irrigation programs, SURFACE and SURMOD, were also written at Utah State University in the United States during these years (late 1980s). SURFACE, based on the volume balance model described by Walker and Skogerboe (1987), can be used for borders, basins and furrows. It was included in an FAO irrigation and drainage paper by Walker (1989), and copies of the program are available from FAO, Rome. SURMOD can also be used for borders, basins, and furrows, and with all three of the methods for operating a surface irrigation system (ie, cutback, reuse, and surge flow). The latest version, available from Utah State University, is called SIRMOD II. It gives the user the option of using the kinematic-wave model, the zero-inertia model or the fully hydrodynamic model to simulate surface irrigation.

For sloping open-ended borders, the United States Water Conservation Laboratory published BORDER (Strelkoff et al. 1996). BORDER allows the user to choose from various options for design, operation, and evaluation. It is similar to BASIN in that it obtains its results from graphs constructed with the dimensionless approach of the zero-inertia model (Strelkoff and Shatanawi 1984).

### **2.3.3 Design, operation and evaluation**

All of the computer programs we mentioned in the previous section are useful in solving problems of surface irrigation. The many possible issues that could be addressed ultimately all have to do with design, operation or evaluation.

#### *Design*

Although design deals with a yet-to-be-built irrigation system, field data will depend on the actual physical situation, giving the designer little room for manoeuvre. The site will be known, so there will be some information available

on the soil infiltration characteristics, the crops that will probably be grown and the surface flow resistance. It is the combination of soil and crop data with climatic data that will determine the most reasonable irrigation application depth. If the data is insufficient, the designer must either collect more in the field or make professional estimates. The same conditions, but with more choice for the designer, apply to the parameters for field slope, furrow spacing and geometry. In other words, the field parameters are given, assumed or estimated.

Design can then be focused on the determination of one or more of the decision variables: flow rate, field length, field width and/or cutoff time. Depending on the situation, either the flow rate is fixed and with most of the available computer programs one can calculate field dimension and cutoff time, or the field dimensions are fixed and the computer programs can calculate the flow rate and cutoff time. Performance indicators are always obtained as a result.

### *Operation*

Operation takes place in an existing situation, which means that all relevant field parameters including the field dimensions are known. Most of the published computer programs can be used to calculate the remaining decision variables of flow rate and cutoff time. Performance indicators are always obtained as a result.

The degree of freedom a farmer has in operating a surface irrigation system depends on the local situation, which is dictated by the design of the system and the method of operation. If, for example, the system is operated according to a strict rotational distribution, the full flow rate and the total duration will be fixed and the farmer will only be able to operate within these limits. He could decide to split up the flow for various units within his own farm and juggle with the cutoff time per unit. In addition, the cutback and reuse methods of operation can offer the farmer an extra measure of flexibility.

### *Evaluation*

In this book, the term "evaluation" stands for assessment of irrigation performance, the performance indicators being adequacy, efficiency and uniformity. In this case, evaluation can be extended to cover quality of design and method of operation. We also use the term to denote analysis of an existing situation for all known data: field parameters, field dimensions, flow rate and cutoff time. Then, evaluation indicates the measure of the appropriateness of that situation and the modifications that could improve irrigation performance.

The terminology we use differs from that in the American literature, where there could be a distinction between analysis, synthesis and evaluation. Used in this way, "analysis" is virtually synonymous with "simulation": all variables are known and the resulting irrigation performance is analysed. "Synthesis"

means "to give help in designing", where "designing" is something that affects either the field (dimensions, slope, furrow spacing) or the operational variables (flow rate, cutoff time, cutback flow rate). In American usage "analysis" is not well defined and sometimes used to indicate the inverse process of determining the infiltration characteristics from a measured irrigation performance in the field.

## 3 Parameters and variables involved

In this chapter we discuss the various parameters and variables involved in the surface irrigation process, focusing somewhat more on simulation aspects. We have categorised the many variables involved in surface irrigation according to whether they are field parameters, decision variables or evaluation variables. Field parameters are situational data (i.e. data that describe the field situation) and are not variables in the true sense of the word, because a design engineer or farmer cannot assign them another value. Decision variables are those parameters or variables that an irrigation designer or operator can adapt to find the best irrigation performance for given or selected field parameters. Evaluation variables are basically yardsticks for determining which combination of decision variables and field parameters will produce the best irrigation performance.

### 3.1 Field parameters

Field parameters always include the infiltration characteristics, the surface roughness or flow resistance and the required irrigation depth. In border and furrow irrigation, the gradient in the downstream direction is also a field parameter, because the existing natural slope of the land may suggest a field slope, which could be too low for water to advance quickly enough or too steep to avoid erosion. A final choice may be restricted by the cost of land grading or the orientation of the fields, for instance. Finally, in furrow irrigation, the shape and spacing of the furrow are limited-choice field parameters. Furrow spacing is dictated mainly by agronomic requirements; the furrow shape mainly dependent on the available farm equipment and local practice.

#### 3.1.1 Soil infiltration characteristics

The objective of surface irrigation is to allow as much water as possible to infiltrate into the soil to the required depth. Because infiltration largely controls the advance and recession of the surface flow, the infiltration characteristics of the soil constitute a fundamental and independent input parameter for many calculation methods and for all computer simulations.

Soil infiltration properties can be described in different ways. Over the years, the major approaches were based on one-dimensional porous-media flow equations, or on physical considerations, or on empirical relationships. For reasons of simplicity and minimum data requirement, the last-mentioned category has been the most widely used, also in recent irrigation models.

Here, only some of the most commonly used infiltration approaches are discussed, namely the Kostiakov and the Kostiakov-Lewis equations, the SCS and modified SCS intake families, and the time-rated intake families.

### *The Kostiakov equation and the Kostiakov-Lewis equations*

The Kostiakov equation shows the relationship between the *cumulative infiltrated depth* ( $D_i$ ) and the *elapsed time* ( $T$ ) since the start of infiltration. It reads

$$D_i = kT^A \quad (3.1)$$

in which we see an empirical coefficient ( $k$ ) and an empirical exponent ( $A$ ). The derivative of this equation shows the relation between the *instantaneous infiltration rate* ( $I$ ) indicating the infiltration depth per unit time period at time  $T$ . It reads

$$I = kAT^{A-1} \quad (3.2)$$

Figure 3.1a shows the general shape of both relationships. Figure 3.1b shows that both equations give a straight line when they are plotted on double-logarithmic scales. Written in logarithms, Equation 3.1 converts to  $\log D_i = \log k + A \log T$ , with  $A$  being the positive slope of the straight line and  $k$  indicating the intercept with the vertical axis. Equation 3.2 converts to a similar linear expression, namely,  $\log I = \log k + \log A + (A-1) \log T$ , but now with  $(A-1)$  being the negative slope of the line. You should be careful when you change units  $T$  and  $D_i$  because the empirical exponent  $k$  is not dimensionless but has the dimension  $\text{depth}/\text{time}^A$  instead, as one can see in Equation 3.1.

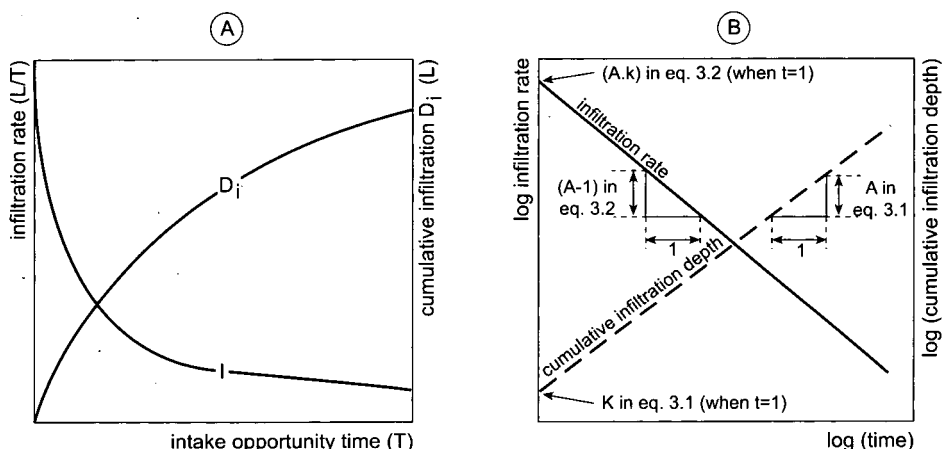


Figure 3.1 Cumulative and instantaneous infiltration versus time (after Kostiakov)



A disadvantage of the Kostiakov equation is that the infiltration rate approaches zero when values of  $T$  are high. As this is often incorrect a constant term can be added to the infiltration rate, which then becomes

$$I = kAT^{A-1} + f_0 \quad (3.3)$$

with a corresponding cumulative infiltrated depth

$$D_i = kT^A + f_0T \quad (3.4)$$

in which the constant term  $f_0$  is called the *basic infiltration rate*, ie, the long-term constant infiltration rate. Equation 3.3 is called the Kostiakov-Lewis infiltration equation.

### *SCS intake families*

To impose a limited number of standard classes on the widely varying infiltration coefficients and exponents, the US Soil Conservation Service developed several "intake families" of soil types according to soil texture and infiltration rate (US Department of Agriculture 1974). These intake families can be expressed numerically using the following equations

$$D_i = aT^b + c \quad (3.5)$$

and

$$I = abT^{b-1} \quad (3.6)$$

Equation 3.5 is intermediate between the Kostiakov equation and the Kostiakov-Lewis equation. A comparison shows that the Kostiakov equation (Equation 3.1) has no basic infiltration rate at all, and that one of the Kostiakov-Lewis equations (Equation 3.4) has  $f_0T$  instead of  $c$ . The constant  $c$  in Equation 3.5 equals 0.275 inch or 6.985 mm.

Table 3.1 gives the SCS family numbers (0.05, 0.1, 0.15, and so on) and their corresponding values for  $a$  and  $b$  according to Equation 3.5. The SCS family numbers approximate the long-term infiltration rate in inches per hour according to Equation 3.6. In Table 3.1, the data for basins and borders come from the SCS National Engineering Handbook that was published in 1974 and the data for furrows come from a later version (USDA 1983). The two sets of data show slight differences, the latter does not explain why. The only clue in the chapter on furrow irrigation – which is the source of the data – is in the statement that: "The intake curves developed for furrow or corrugation irrigation have the same general shape as curves developed for the border and contour-ditch methods. The furrow curves on a specific site are not necessarily the same as the border curves, but should generally be parallel."

Table 3.1 Values of a and b in Eq. 3.5 for SCS intake families

Intake Family	Basins / Borders*			Furrows**		
	a (in/min <sup>b</sup> )	a (cm/min <sup>b</sup> )	b	a (in/min <sup>b</sup> )	a (cm/min <sup>b</sup> )	B
0.05				0.0210		0.0681
0.10	0.0244	0.0620	0.661	0.0244	0.0620	0.6610
0.15				0.0276		0.6834
0.20				0.0306	0.0777	0.6988
0.25				0.0336		0.7107
0.30	0.0368	0.0935	0.721	0.0364	0.0925	0.7204
0.35				0.0392		0.7285
0.40				0.0419	0.1064	0.7356
0.45				0.0445		0.7419
0.50	0.0467	0.1186	0.756	0.0471	0.1196	0.7475
0.60				0.0520	0.1321	0.7572
0.70				0.0568	0.1443	0.7656
0.80				0.0614	0.1560	0.7728
0.90				0.0659	0.1674	0.7792
1.00	0.0701	0.1781	0.785	0.0703	0.1786	0.785
1.50	0.0899	0.2283	0.799	0.0899	0.2283	0.799
2.00	0.1084	0.2753	0.808	0.1084	0.2753	0.808
3.00	0.1437	0.3650	0.816			
4.00	0.1750	0.4445	0.823			

\* Source: USDA (1974); \*\* Source: USDA (1983)

### *Modified SCS intake families*

It is possible to modify the SCS intake families for use with the Kostiakov equation, by linearising the original curves between two particular depths. Fangmeier and Strelkoff (1979) made such a linearisation based on infiltration depths of 50 and 100 mm. Table 3.2 shows the results of these operations.

According to Walker (1989), it is also possible to modify the SCS intake families to fit the Kostiakov-Lewis equation (Equation 3.1) for furrows. This has been done by determining a different value of  $f_0$  for each intake family and

Table 3.2 Modified SCS intake families for the Kostiakov equation for basins

Intake family	Coefficient k			A	Soil texture
	(in/hr <sup>A</sup> )	(mm/min <sup>A</sup> )	(mm/hr <sup>A</sup> )		
0.1	0.49	1.10	12.57	0.595	clay, silty clay
0.3	0.90	1.59	22.76	0.650	silty clay, clay loam
0.5	1.25	1.93	31.76	0.684	clay loam, loam
1.0	2.01	2.84	51.13	0.706	loam, silt loam
1.5	2.65	3.56	67.32	0.718	silt, sandy loam
2.0	3.25	4.22	82.46	0.726	sandy loam, fine sand
3.0	4.32	5.41	109.68	0.735	fine-to-medium sand
4.0	5.37	6.59	136.37	0.740	medium-to-coarse sand

Table 3.3 Kostiakov-Lewis infiltration parameters for modified SCS intake families for furrows and borders (after Garbi 1984)

Intake family	$k \text{ (m/min}^A\text{)}^*$	A	$f_0 \text{ (m/min)}$	Soil type*
0.05	0.00426	0.258	0.000022	Clay
0.10	0.00383	0.317	0.000035	
0.15	0.00360	0.357	0.000046	
0.20	0.00346	0.388	0.000057	
0.25	0.00337	0.415	0.000068	Clay loam
0.30	0.00330	0.437	0.000078	
0.35	0.00326	0.457	0.000088	
0.40	0.00323	0.474	0.000098	
0.45	0.00321	0.490	0.000107	Silty loam
0.50	0.00320	0.504	0.000117	
0.60	0.00320	0.529	0.000136	
0.70	0.00321	0.550	0.000155	
0.80	0.00324	0.568	0.000174	Sandy loam
0.90	0.00328	0.584	0.000193	
1.00	0.00332	0.598	0.000212	Sandy
1.50	0.00361	0.642	0.000280	
2.00	0.00393	0.672	0.000339	

\* Source: Walker (1989)

then calculating the values of A and k to equal the values of the original SCS intake families (Garbi 1984, as mentioned in Walker 1989). Table 3.3 shows the results of these operations.

#### *Time-rated intake families*

According to Merriam and Clemmens (1985), the SCS intake families in Table 3.1 do not correspond well with field data on irrigated borders and furrows. They suggest using "time-rated" intake families instead, which are based on the time it takes irrigation water to infiltrate 100 mm: a typical target irrigation depth. From their field data, they approximated the value of the exponent A in the Kostiakov equation (Equation 3.1) as

$$A = 0.675 - 0.2125 \log T_{i(100)} \quad (3.7)$$

where  $T_{i(100)}$  is the time (in hrs) that it takes to infiltrate a depth of 100 mm. You can get the set of time-rated intake families of Table 3.4 by calculating A for different times  $T_{i(100)}$  with Equation 3.7 and then inserting this A into the Kostiakov equation for  $D_i = 100$  mm.

#### *Obtaining field measurements of infiltration*

Field measurements of infiltration can be helpful in determining the correct infiltration characteristics of the soil, which is often a major problem in surface irrigation. The most common method is to collect point data with a ring

Table 3.4 Time-rated intake families with k and A fitting the Kostiakov equation (Merriam and Clemmens 1985)

$T_{i(100)}$		Coefficient k		Exponent A
Hrs	Min	mm/hr <sup>A</sup>	mm/min <sup>A</sup>	
0.5	30	167.0	8.10	0.739
1	60	100.0	6.31	0.675
2	120	65.5	5.37	0.611
4	240	46.8	4.98	0.547
8	480	36.6	5.07	0.483
16	960	31.3	5.63	0.419
32	1920	29.2	6.83	0.355

or double-ring infiltrometer, as described in detail in various standard field-irrigation handbooks. This infiltrometer method enables field data to be collected that give the values of the soil infiltration parameters. Using the Kostiakov equation, data on infiltrated depths and time can be plotted on logarithmic scales, making it possible to determine the values of A and k either by regression or by taking them directly from the graphs in Figure 3.1b.

The major disadvantage of an infiltrometer method is that it yields point measurements, whereas one needs to know average values for the entire field. To obtain such values, you can collect data from many points on the field and then determine average infiltration parameters. You can also collect data using the inflow-outflow method, which is suitable for all irrigation methods, or by using the blocked-furrow or recycling-furrow-infiltrometer method, which is specifically for furrows. For more information, see the standard handbooks (eg, Walker and Skogerboe 1987, pages 88-92).

A more recent method and perhaps the most practical of all, is to collect advance data from the entire field and then insert them into the inverse use of a simulation model (including the governing infiltration equations) to calculate the "average" field-infiltration parameters. The type of data to collect and the processing thereof will depend on the irrigation method and the simulation model you use. Clemmens (1981) reviews various approaches to processing data collected from borders and, in a subsequent publication (Clemmens 1982), he presents a method for evaluating infiltration in borders. Maheshwari et al. (1988) describe how to use the volume balance model on borders. For furrows, Fangmeier and Ramsey (1978) use the volume balance model to determine the parameters in the Kostiakov-Lewis equation. Elliot and Walker (1982) also use the volume balance model for the same purpose, but they reduce the amount of work required by using a two-point method. It involves the relatively easy task of collecting data on the following: constant inflow rate; advance time at halfway the furrow length; advance time at the end of the furrow; furrow spacing; and stable surface runoff flow. You can then determine the average of A and k in the Kostiakov equation for furrows.

### 3.1.2 Flow resistance

*Flow resistance* ( $n$ ) is a basic input parameter in simulations of surface irrigation, which has a direct effect on flow velocity and, consequently, on advance time, infiltration pattern and total irrigation performance. The higher the flow resistance the longer the advance time. The longer the advance time the more non-uniform the infiltrated-depth distribution.

Manning's roughness coefficient  $n$  meant for steady uniform flow in canals is also commonly used for surface irrigation. The 1974 edition of the SCS National Engineering Handbook recommended values of Manning's roughness coefficient for basins and borders (Table 3.5). These have appeared in nearly all work on surface irrigation ever since, without much discussion or detailed field research. Results of research done (Linderman and Stegman 1969; Michael and Pandya 1971; Roth et al. 1974; Ree and Crow 1977) are not conclusive, but suggest that the recommended  $n$ -values of the SCS are acceptable even though the actual  $n$ -values are sometimes higher.

Clemmens (1979) confirmed both observations when he verified the zero-inertia model for border irrigation. On sloping borders, Clemmens (1991) found high  $n$ -values for long fields with sandy soils. In addition, he found values of  $n = 0.15 - 0.20$  for barley (slope = 0.003),  $n = 0.18-0.23$  for wheat (slope = 0.003), and  $n = 0.13-0.27$  for alfalfa (slope = 0.009). His findings compelled us to include the  $n$ -value 0.20 in Table 3.5. Note that these are for basins and borders only.

When investigating furrow infiltration, Fangmeier and Ramsey (1978) found  $n$ -values that ranged between 0.02 and 0.04. The 1983 edition of the SCS National Engineering Handbook states that a value of  $n = 0.04$  is appropriate for furrows. It gives no other details. Unlike basins and borders, furrows have no crops growing in them (if all is well), so the range of  $n$ -values for furrows is smaller. Walker (1989) uses  $n = 0.04$  in all of his calculation examples for furrow irrigation.

Table 3.5 Recommended values of  $n$  (Manning's roughness coefficient) for basins and borders

$n$ value	Conditions
0.04	Smooth, bare soil surface; row crops
0.10	Drilled, small-grain crops, drill rows in flow direction
0.15	alfalfa, mint, broadcast small grains
0.20	dense alfalfa or alfalfa on long fields without secondary ditches
0.25	dense sod crops and small grains, drilled perpendicular to flow direction

### 3.1.3 Required depth

*Required depth* ( $D_{\text{req}}$ ) is another basic input parameter in simulations of surface irrigation. We briefly summarise the most common methods for determining this parameter and refer the reader to irrigation handbooks for more information.

The maximum required depth can be determined from the total soil-moisture holding capacity, ie, the total moisture available between field capacity and wilting point (TAM) and the allowable depletion fraction thereof, called the readily available moisture content (RAM). Together with an assumed rooting depth, this gives the maximum depth to which the soil can dry out and the depth the irrigation water supply must reach by the end of an irrigation interval. For a given or estimated evapotranspiration rate, this maximum depth fixes the maximum irrigation interval.

This method will satisfy the crop water requirements completely. It is possible, however, to accept a sub-optimal supply (with potential yield reduction), which is the method behind "protective irrigation" in India. In other cases (eg, "warabandi" distribution; see Malhotra 1982), the local irrigation authority makes a roster that fixes the flow rate, irrigation interval and duration of each farmer's turn, without taking crop water requirements into consideration. Here, it is water availability rather than water requirements that fixes the value of  $D_{\text{req}}$  and under-irrigation (relative to the crop water requirements) is normal.

Computer programs like CROPWAT (Smith 1992) and CRIWAR (Bos et al. 1996) can be used to compute crop water requirements and assess possible scheduling alternatives. Results of these programs can be used as target depth input in surface irrigation programs.

### 3.1.4 Field slope and non-erosive velocity

For graded borders and furrows, the *field slope* ( $S_0$ ) should not be too high (to prevent erosion) or too low (to prevent slow advance). The engineer may have problems ensuring the best field slope if the cost of land grading is high or if the orientation of the fields is unfavourable. A relatively flat slope may pose drainage problems in areas of high rainfall intensity. For borders, the most suitable slopes are usually less than 0.5 per cent. But, if planted with sod crops, slopes up to 4 per cent can also work well. For furrows, suitable slopes vary between 0.05 and 1 per cent. Slopes up to 2 per cent can work for small furrows and corrugations.

Erosion is not a problem on most border slopes, except maybe at the head, where water velocity depends on how the total inflow is supplied to the field (point inflow or inflow distributed uniformly over the entire width of the border). Certain provisions have to be made locally in the field to avoid erosion.

For graded furrows, this issue is slightly different because flow is concentrated in a smaller section. The flow velocity in graded furrows should not exceed a *maximum non-erosive* value ( $v_{\max}$ ). The value of  $v_{\max}$  depends on the soil type. Usually, it ranges between about 8 m/min in erosive silt soils and about 13 m/min in more stable clay and sand soils, with the highest values occurring in the first part of the furrow, down the inlet (Walker and Skogerboe 1987). In simulations of flow in furrows, the furrow slope and the maximum non-erosive flow velocity are related to the *maximum permissible inflow* ( $q_{\max}$ ) with the equation

$$q_{\max} = \left( v_{\max} C_1 \left( \frac{n}{S_0^{0.5}} \right)^{C_2} \right)^{\frac{1}{1-C_2}} \quad (3.8)$$

where  $n$  is the flow resistance and  $S_0$  is the furrow slope. The coefficients  $C_1$  and  $C_2$  depend on the furrow geometry (for details, see Appendix B). Equation 3.8 is then used to check whether the actual flow velocity will exceed the maximum non-erosive flow velocity, given a certain inflow rate and furrow slope.

### 3.1.5 Furrow spacing

In furrow irrigation, the spacing of the furrows is a limited-choice field parameter. It is usually not the irrigation engineer who dictates spacing, but rather the agronomic constraints like the required distance between crop rows and the width of farm implements. *Furrow spacing* ( $W_s$ ), the distance from centre to centre of two adjacent furrows, is in fact a dual-purpose parameter. It is clearly a field dimension used primarily to convert volumes to depths ( $D = Q / [LW_s]$ ), but it is also an input that assists in the modelling of the infiltration process.

In simulations of flow in furrows, it is assumed that infiltration from the furrow spreads out over the width of the furrow spacing and then is entirely vertical below a certain depth.  $W_s$  is used to convert the  $A$  and  $k$  values corresponding to the modified SCS intake families.

### 3.1.6 Furrow geometry

To simulate surface flow, there must be a means to relate the flow rate to the flow cross-section. For basins and borders the situation is fairly simple, flow is assumed to be uniform over the field width, therefore it is a two-dimensional process: only the head-to-tail direction and the flow depth are involved. Infiltration happens only in a vertical direction and so can be calculated per unit of width.

Furrows are a bit more complicated. Furrows are miniature channels in which the relation between the top width of the flow section and the flow

depth varies with the flow size and with the various shapes the furrow channel can have. Moreover, infiltration takes place along the wetted perimeter, which varies with the flow depth. Consequently, the geometric (or cross-sectional) parameters of furrows require further scrutiny.

In simulations of flow in furrows, it is common practice to use Manning's equation to describe surface flow. Manning's equation reads

$$Q = \frac{1}{n} AR^{2/3} S^{1/2} \quad (3.9)$$

in which  $Q$  is the furrow flow rate,  $S_0$  is the furrow slope,  $n$  is the flow resistance,  $A$  is the wet cross-section, and  $R$  is the hydraulic radius. The section factor  $AR^{2/3}$  is then related to the flow depth assuming simple power functions (Fangmeier and Ramsey 1978; Elliott et al. 1982; Walker and Skogerboe 1987).

### 3.2 Decision variables

Decision variables are those parameters or variables that a design engineer can manipulate to find the best irrigation performance for given or selected field parameters. The decision variables in surface irrigation are normally the field dimensions (length and width), the flow rate and the cutoff time. Of course, there are also limits to the values of these variables: the field length has to fit in the existing infrastructure; the flow rate must be such that a farmer can handle it; and the cutoff time can be limited to a particular period (eg, to the daylight hours). The main design consideration in surface irrigation is usually the choice of the appropriate combination of field dimensions, flow rate, and cutoff time.

#### 3.2.1 Field dimensions

For basins and borders, the field dimensions are width ( $W$ ) and length ( $L$ ). For furrows, there is only one field dimension: the furrow length. Furrow spacing is important only in the context of field parameters. You should realise that, in practice, it is not always possible to choose an optimum field length. Field length is subject to limitations from the local infrastructure (eg, roads, canals, slopes and so on). For basins, there is no best size or length. If there is a given flow rate, obviously increasing the length of the basin will lower the irrigation performance because the advance time will be longer. A higher flow rate, however, will permit the designer to increase the length of the basin. Nevertheless, at a certain point, increasing the flow rate will no longer enable the designer to extend the length of the basin. Thus, one can speak only of a maximum practical length (see Chapter 8, Section 1.2).



The criteria for best field length are different for borders and furrows, at least when these are open-ended. If a field with open-ended borders or furrows is too long, irrigation performance will be low because the advance time will be long, causing uneven infiltration and considerable losses to deep percolation at the upstream end of the field. If a field is too short, surface runoff will be too high. So, there will be an optimum length for a field with open-ended borders and furrows. It is the length for which the sum of deep percolation and surface runoff losses is minimum, making the irrigation application efficiency maximum.

In simulations, field dimensions can be either the input to determine the required flow rate, or the output of such a simulation, to assist a designer/evaluator who needs to know the best field dimensions for a given flow rate.

### 3.2.2 Flow rate

For basins and borders, there is a total flow rate ( $Q_0$ ) for the field. The flow rate is divided by the field width to obtain a unit flow rate ( $q_0$ ) per metre of width, and the result is used in the theoretical analysis. For furrows,  $q_0$  is the rate of inflow into one furrow, which is the unit flow rate per width of one furrow spacing.

Flow rate is a key variable that affects the outcome of an irrigation event because it influences the advance time of the inflow and, consequently, the irrigation uniformity, efficiency, and adequacy. The flow rate should not be too low, because then it will not reach the end of the field. Nor should it be too high. For basins and borders, there is a practical upper limit above which performance will not improve (see Chapter 8, Section 1.1). For furrows, the flow rate should not be too high to prevent scouring. There is an optimal flow rate (just as there is an optimal field length) for open-ended borders and furrows. This is the rate at which the sum of deep percolation losses and surface runoff losses is minimum.

Inflow can enter borders and basins through a point inlet (one inlet structure), or there can be a more uniform application of flow over the head end of the field by digging a head ditch from which the field receives the water directly, either from overflow or from inlets or siphons. If there is a point inlet, energy-dissipating measures may be necessary to avoid erosion from large flows.

In existing situations, the flow rate is usually relatively easy to measure. Common flow sizes (less than 50 l/s) can be measured using portable RBC flumes. Bos, Replogle, and Clemmens (1984) describe these flumes in detail. Table 3.6 shows their principal characteristics. The table also shows that the standard RBC flumes are suitable for measuring flows of 1 to 50 l/s. Measuring larger flows in basins and borders can be done with a custom-made portable flume. Siphons used in furrows, borders or basins can also be used to measure the flow.

Table 3.6 Properties of five standard RBC flumes (after Bos, Replogle, and Clemmens 1984)

Throat width (in mm)	Flow range (l/s)		Approximate head loss (in mm)
	Minimum	Maximum	
50	0.03	1.5	10
75	0.07	4.3	15
100	0.16	8.7	20
150	0.40	24	30
200	0.94	49	40

In simulations, flow rate can be either an input (chosen by the designer/evaluator or dictated by the existing supply conditions) or the outcome of one or more simulations that the designer/evaluator makes while searching for the best flow rate.

### 3.2.3 Cutoff time

Cutoff time ( $T_{co}$ ) is the amount of time that elapses from the start of irrigation to the cutoff of the inflow. In simulations, cutoff time can be either input or output, as with the other decision variables.

Cutoff for all three irrigation methods occurs usually some time after the end of the advance time so as to obtain infiltration to the required depth at the downstream end of the field. If cutoff time is substantially later than advance time, this will have a clear effect on the deep percolation and surface runoff losses. If cutoff occurs too early, infiltration to the required depth will often not happen at the end of the field. So, clearly, there are limits to the value that you can choose for the cutoff time, to achieve good irrigation performance.

Furthermore, cutoff time can be subject to practical restrictions. If, for example, there is a strict rotational distribution within the tertiary unit, the cutoff time is fixed by the rotational roster.

### 3.2.4 Cutback ratio, advance time ratio and tailwater reuse ratio

The cutback ratio, advance time ratio, and tailwater reuse ratio enter the simulation picture when you reduce inflow after some time or when you reuse tailwater runoff. This means that the three ratios are not relevant to basin irrigation.

The *cutback ratio* (CBR), which is defined as the ratio of reduced flow rate or *cutback flow rate* ( $Q_{cb}$ ) to initial flow rate ( $Q_o$ ), must be such that the reduced flow is sufficient to keep the entire field length wetted for the required time, while reducing the surface runoff. For ease of simulation, the

usual assumption is that cutback occurs when the water has reached the end of the field. In simulations, the CBR is always input.

The *advance time ratio* (ATR) is defined as the ratio of advance time ( $T_a$ ) to cutoff time ( $T_{co}$ ). ATR is of special interest in cutback furrow or border systems. A small advance ratio means a fast advance, denoting a high flow rate. In simulations, ATR can be either input or output.

The *tailwater reuse ratio* (TRR) is defined as the portion of the surface runoff that is reused. With the TRR, one can calculate the application efficiency directly. A TRR of 1.0 though ideal may not always be possible to achieve because the costs involved may be too high. In simulations, the TRR is always input.

### 3.3 Evaluation variables

Evaluation variables are basically yardsticks for determining the combination of decision variables and field parameters that will produce the best irrigation performance. In most cases, the quality of an irrigation application is judged in terms of *adequacy* (ie, whether sufficient water was supplied to the field), *efficiency* (ie, a relative measure of how much water is "lost" during irrigation), and *uniformity* (ie, the distribution of infiltrated water depths over the length of the field). The primary irrigation performance indicators are: storage efficiency, application efficiency and distribution uniformity. Although there have been attempts at standardisation (eg, Bos 1985, and Kruse 1978), the literature still contains a variety of surface irrigation performance indicators and their definitions. All performance indicators are directly related to the pattern of infiltrated depths over the length of the field.

#### 3.3.1 Water layer depths

In this book, we express all amounts of water in terms of water layer depths (D). We calculate these as volumes divided by the *field area* (A), which for basins and borders is length (L) times width (W) and for furrows is length (L) times furrow spacing ( $W_s$ ).

An important variable is the *required depth* ( $D_{req}$ ) or target depth, which is the depth of water we want to store in the soil. This is not usually the same as the *applied depth* ( $D_a$ ),

$$D_a = \frac{Q_o T_{co}}{A} \quad (3.10)$$

in which  $Q_o T_{co}$  equals the applied volume (flow rate times cutoff time). The applied depth infiltrates the field area either partly or entirely. This infiltrat-

ed part is expressed as *average infiltrated depth* ( $D_{av}$ ).  $D_{av}$  equals  $D_a$  if there is no surface runoff, otherwise  $D_{av} < D_a$ , and the difference is the *surface runoff depth* ( $D_{sr}$ ).

Even when  $D_{av}$  is more than  $D_{req}$ , there may still be a part of the field (usually the lower end) that is not properly wetted. The average depth of water that is actually stored in the target zone  $D_{req}$  is the *storage depth* ( $D_s$ ). When the target zone is entirely filled,  $D_s$  will equal  $D_{req}$ . If  $D_s < D_{req}$ , then there is under-irrigation. On the other hand, some of the infiltrated water may exceed  $D_{req}$ . Then, the depth of the water is called the “*deep percolation depth*” ( $D_{dp}$ ). Infiltrated depths are expressed in terms of an imaginary water layer; they do not refer to a physical depth below the field’s surface. The real physical depth to which irrigation water infiltrates is dependent on the soil porosity and the initial soil moisture content. As an example, let us assume that  $D_{av}$  is 100 mm. If 20 per cent of the soil volume is available for moisture storage, and if half of this is already filled with water, it means that a  $D_{av}$  of 100 mm is actually wetting a soil layer of 1000 mm.

### 3.3.2 Adequacy

We express the adequacy of an irrigation turn in terms of *storage efficiency* ( $E_s$ ), which is defined by Hart et al. (1980) as the ratio between the storage depth and the required depth, or

$$E_s = \frac{D_s}{D_{req}} \quad (3.11)$$

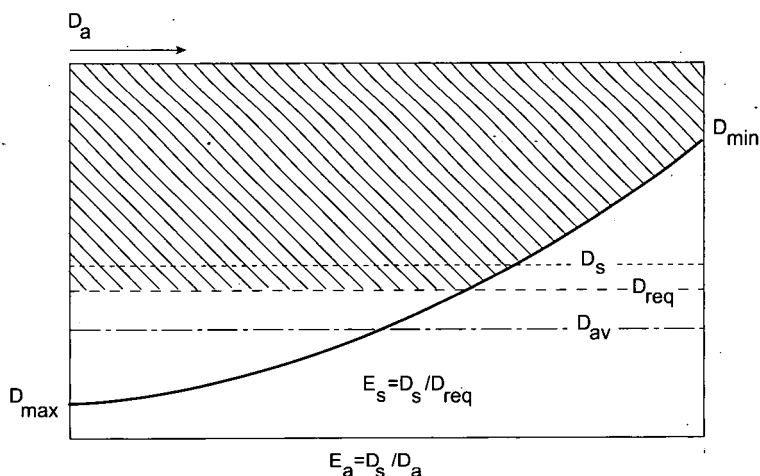


Figure 3.2 Storage efficiency

The purpose of an irrigation turn is to meet at least  $D_{\text{req}}$  over the entire length of the field. If this purpose is achieved, then  $D_s = D_{\text{req}}$  and  $E_s = 1$ . This means that the *minimum infiltrated depth* ( $D_{\text{min}}$ ) will be equal to or larger than  $D_{\text{req}}$ . Figure 3.2 shows a situation in which the purpose has not been achieved because  $D_{\text{min}} < D_{\text{req}}$ . The area with the cross-hatching indicates the depth of the water that was added to achieve  $D_{\text{req}}$  (the numerator). Converting this depth to an average depth over the entire length of the field, we see that it is equal to  $D_s$ . As this is less than  $D_{\text{req}}$ , so it follows that  $E_s < 1$ .

### 3.3.3 Efficiency

The *application efficiency* ( $E_a$ ) is a common yardstick of relative irrigation losses. Hart et al. (1980) define it as the depth added to the target zone divided by the applied depth, or

$$E_a = \frac{D_s}{D_a} \quad (3.12)$$

This definition is valid for all situations and all irrigation methods. Figure 3.3 shows the application of this definition of  $E_a$  for the various possible infiltration profiles. The differences are related to the relative values of  $D_{\text{min}}$ ,  $D_s$ ,  $D_{\text{av}}$  and  $D_{\text{req}}$ .

In Figure 3.3a (the design case),  $D_{\text{min}} = D_{\text{req}}$  so  $D_s = D_{\text{req}}$ , consequently  $E_a = D_{\text{req}} / D_a$ , and  $E_s = 1$ . In Figure 3.3b,  $D_{\text{min}} > D_{\text{req}}$ , meaning that there is over-irrigation, while  $E_s = 1$  and  $E_a = D_{\text{req}} / D_a$ . For basins,  $D_a = D_{\text{av}}$  and  $E_a = D_{\text{req}} / D_{\text{av}}$ . For under-irrigation, however, the situation is more complicated because there are three possibilities. In all three cases,  $D_{\text{min}} < D_{\text{req}}$  and  $D_s < D_{\text{req}}$  (thus  $E_s < 1$ ), but the relative values of  $D_s$ ,  $D_{\text{av}}$ , and  $D_{\text{req}}$  are different. In Figure 3.3c there is so much deep percolation that  $D_{\text{av}} > D_{\text{req}}$ , but in Figure 3.3d there is so little deep percolation that  $D_{\text{av}} < D_{\text{req}}$ . In Figure 3.3e there is under-irrigation along the entire length of the field, and the *maximum infiltrated depth* ( $D_{\text{max}}$ ) is less than  $D_{\text{req}}$ , and  $D_s = D_{\text{av}}$ .

In fact,  $1 - E_a$  indicates the fraction of the applied water that is "lost" (ie, the fraction that is not actually stored in the target zone). Such losses can be due to surface runoff and deep percolation, for which we use the indicators below. In borders and furrows without reuse, the *surface runoff ratio* (SRR) equals the surface runoff depth divided by the applied depth, or

$$\text{SRR} = \frac{D_{\text{sr}}}{D_a} \quad (3.13)$$

The fraction of water that is lost to deep percolation is expressed by the *deep*

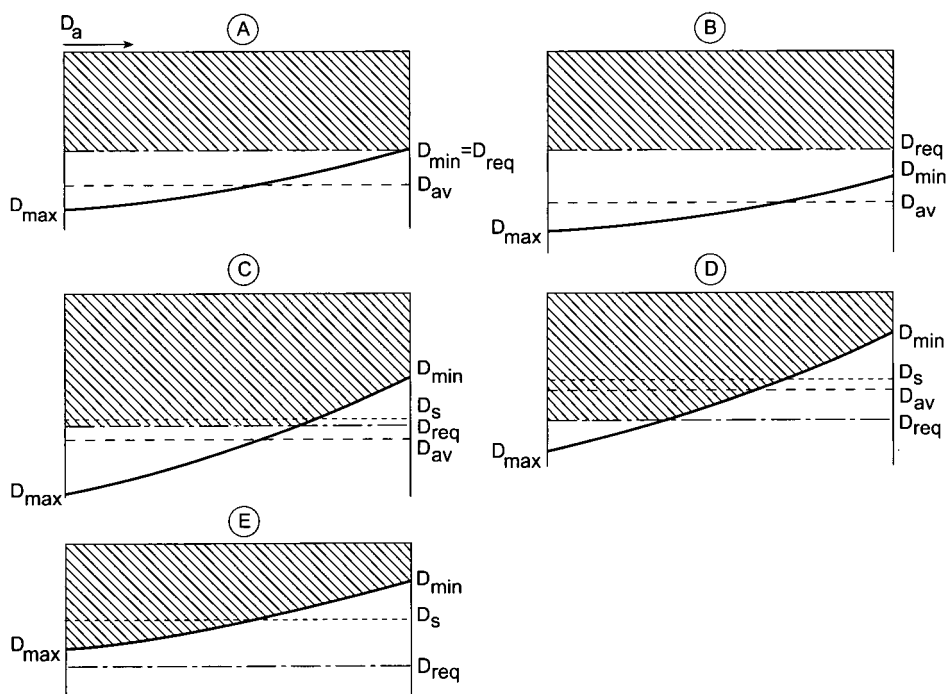


Figure 3.3 Possible infiltration profiles

*percolation ratio* (DPR), which is defined as the deep percolation depth divided by the applied depth, or

$$\text{DPR} = \frac{D_{dp}}{D_a} \quad (3.14)$$

Because both of these indicators have the same  $D_a$  in the denominator, it follows that  $(1 - E_a) = \text{DPR} + \text{SRR}$ , or  $E_a = 1 - \text{DPR} - \text{SRR}$ .

If there is runoff, the infiltrated fraction of the applied depth is  $(1 - \text{SRR})$ . The literature gives no indicator for the part of the infiltrated water that goes to deep percolation. DPR above refers to  $D_a$  and not to a lower  $D_{av}$  or  $D_{req}$ .

### 3.3.4 Uniformity

To get a complete picture of an irrigation performance you need to know more than just the indicators above, because these are averages taken over the entire length of the field. Although different cases might produce the same results for  $E_s$  and  $E_a$  their distribution patterns could differ. One indicator

used to represent the pattern of the infiltrated depths along the field length is the *distribution uniformity* (DU) (see Kruse 1978), which is defined as the minimum infiltrated depth divided by the average infiltrated depth, or

$$DU = \frac{D_{\min}}{D_{av}} \quad (3.15)$$

Because the distribution uniformity involves neither  $D_{req}$  nor  $D_a$ , it cannot give an indication of irrigation adequacy and losses. Nevertheless, in level basins  $D_{av} = D_a$ , and when  $D_{\min} = D_{req} = D_s$ , then  $DU = E_a$ .

The literature on irrigation performance mentions other indicators for uniformity of distribution. One of these is a modified form of the indicator above that uses the infiltrated depth in the lower quarter of the field instead of the minimum infiltrated depth (in the far end). This is called the low-quarter distribution uniformity (LQDU), which we will not be discussing any further in this book. We do, however, discuss another frequently mentioned indicator for uniformity, namely, Christiansen's *uniformity coefficient* (UC), which is defined as

$$UC = 1 - \sum \left( \frac{|D_i - D_{av}|}{nD_{av}} \right) \quad (3.16)$$

For  $n$  points along the length of the field, UC gives the average of all differences between the infiltrated depths and the average depth (Figure 3.4).

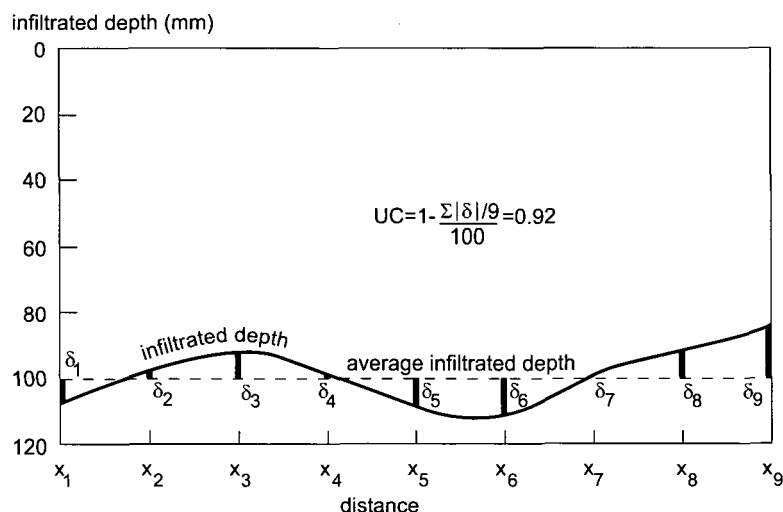


Figure 3.4 Christiansen's uniformity coefficient





## 4 The SURDEV package

The SURDEV program package that accompanies this book comprises three programs: BASDEV (for level basins), BORDEV (for sloping borders) and FURDEV (for graded furrows). Together, they enable the user to design, operate and evaluate surface irrigation systems. All three of these programs are updated versions of earlier programs. BASDEV is the successor to versions 1 and 2 of BASCAD, the mathematical model for basin irrigation, which was published as ILRI Publication 43. It combines a variant of the Eulerian control-volume approach (Walker and Skogerboe 1987) and a modified zero-inertia approach to modelling the advance phase. Programming details of BASDEV can be found in Appendix A.

BORDEV and FURDEV are the updates of the BISDEV program for border irrigation and the FISDEV program for furrow irrigation, the early unpublished versions of which were written at ILWM. These programs are based on the volume balance model, which uses the approach and techniques described by Walker and Skogerboe (1987) to achieve robust solutions. According to Walker and Skogerboe (1987) and Walker (1989), the accuracy of such a model for sloping furrows is adequate for practical application. Programming details of BORDEV and FURDEV are given in Appendix B.

To make SURDEV user-friendly, we have endeavoured to standardise the individual interfaces of the three programs as much as possible. Nevertheless, some differences were unavoidable because of the characteristics specific to each individual program and the irrigation methods they represent. Individual user manuals follow for each of the programs in Chapters 5, 6 and 7, respectively.

### 4.1 Hardware requirements and installation procedure

You can run SURDEV on IBM-compatible machines with 640 kb of free RAM and a 486DX or higher processor. The programs will work on a 286 or 386 computer, but calculation times may be long, even with a mathematical coprocessor present. A VGA graphics card is necessary, and we recommend a colour monitor. After installation, SURDEV will take up 680 kb of space on your hard disk.

Although the SURDEV package has been developed as an MS-DOS program, you can install and run it in a Windows environment. To install SURDEV, insert the original diskette into a floppy disk drive, which is usually drive A:. Use the Windows explorer to log onto drive A: and double-click install.exe. Alternatively, you can use the Run button in the Start menu and type a:\install, and then click the OK button. You can only install SURDEV on your

hard disk (drives C: or D:). The installation will create a SURDEV folder on the specified drive and folder, with three sub-folders called BASDEV, BORDEV, and FURDEV where the data files of the individual programs are stored.

To run SURDEV, use the Windows explorer to log onto the SURDEV folder and double-click `surdev.exe`. Then select either BASDEV, BORDEV, or FURDEV from the menu that appears and follow the screen suggestions or questions. You will receive a message if there is not enough memory available when you start one of the programs.

## 4.2 Menus, keyboard usage, and function keys

All three programs work from pull-down menus which include the items *Files*, *Units*, *Calculation* and *Quit*. You can select an item from the top bar of the main menu by either moving your cursor to the item and pressing [Enter] or by pressing the highlighted letter. A sub-menu will then appear on the screen. Always use the [Esc] key to go one step up in the menu tree (ie, to return to the previous menu). The cursor will automatically go back to the last item that you chose from that menu.

Usually, you choose the items on the main menu from left to right. If you want to make a new file, however, or if you want to browse through a program, to study its structure and operation, you can skip one or more items and move straight to one that is more to the right. All the programs contain default values for input, so that you can start familiarising yourself with a program anywhere in the menu tree.

The bottom bar of each menu contains a brief description of what you can do with the highlighted menu item at the top. This message appears to the right of a vertical bar. On the left, relevant function keys may appear. You can find more information about most items under the Help key [F1]. The name of the program in which you are working appears on the bottom bar at the far right. A few of the keys perform the same operation in all three programs, namely, the arrow keys, the menu-selection keys and the function keys. The procedure for inputting data is also the same for the three programs.

### *Cursor movement*

- Use the arrow keys to move through the screen text, to go to a menu item, or to go to an input location. The [Home] and [End] keys work only when you are editing a file path or file name.
- The [PgUp] or [PgDn] keys work only when this is indicated on the bottom bar (eg, in the output and view screens).

### *Menu selection*

- Press the [Enter] key to select or confirm the highlighted item. This key will also take you one step down in the menu tree.

- Another method of selection or confirmation is to type the letter highlighted in red.
- The [Esc] key will always take you one step up in the menu tree (to the previous screen).
- To move horizontally through the first sub-menus, you can use the left and right arrow keys. You do not need to press [Esc] before doing so.

#### *Function keys*

The following function keys are standard in the three programs:

- [F1] to get HELP (information) for various items, only when indicated in the bottom bar;
- [F2] to RUN the calculations after you have given or edited all input, under *Calculation*;
- [F3] to see a GRAPHical presentation of the results, when in the output screen;
- [F4] to SAVE a file or append a run, when in the output screen;
- [F5] to produce a "PRINT file" only with the *View/Print* option of the *Files* menu, which can be via a direct print-out, a word processor file, or a spreadsheet file;
- [F6] to produce a LIST of directories, under *Files*;
- [F7] to DELETE one of the runs in a file, under *Files-View/Print*;
- [F8] to SAVE a GRAPH as a graphical file for separate colour printing, under [F3];
- [F9] to SAVE a GRAPH as a graphical file for separate black-and-white printing, under [F3];
- [F10] to change the PRINTER(PORT), under *Files-View/Pint*, [F5] - printer.

### 4.3 Calculation

*Calculation* is the penultimate item on the main menu bar and we shall start with explaining its workings because this is the purpose and core of the programs. You can start working in the *Calculation* sub-menu immediately to familiarise yourself with the programs. Each program will then use default values, different for each irrigation method, for the input and default selections for all of the other menu items. Or you can start in the *Calculation* menu, if you are going to make a new (not yet existing) file and know that you want to use the default settings for the other menu items.

#### 4.3.1 Calculation modes

You can choose from four calculation modes to run the three programs. The four modes appear when you select the *Calculation* menu (Figure 4.1).

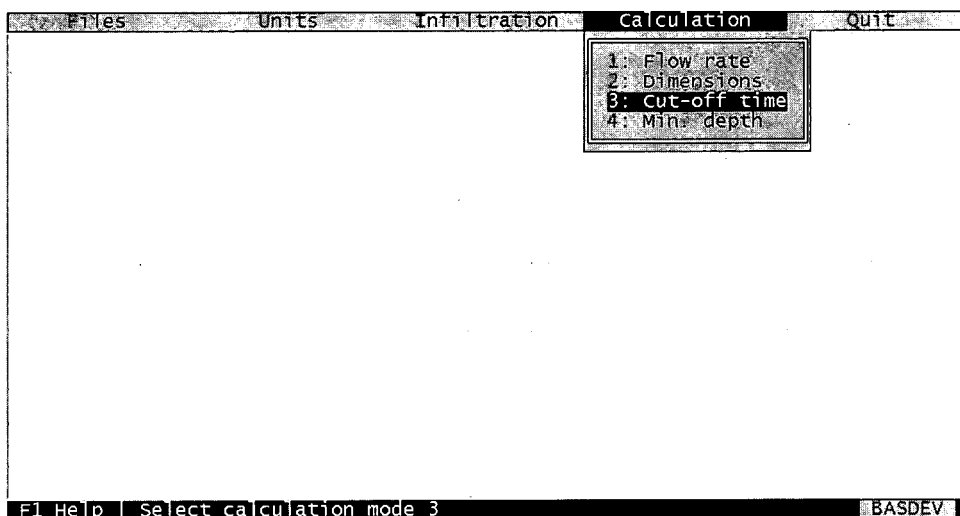


Figure 4.1 Calculation menu with the four modes (Basdev)

Calculation Modes 3 and 4 are the most essential modes for all three programs. Experienced users can go directly to these modes to make their calculations for design, operation and evaluation of surface irrigation systems. Calculation Modes 1 and 2 are meant for the somewhat inexperienced users, but although they give an acceptable result, it is not the best solution and the results need to be refined in Calculation Mode 3 and/or 4. In Calculation Modes 1, 2 and 3 the required infiltration depth is always realised at the basin end, whereas in Calculation Mode 4 this is usually not the case. Although details of the modes of BASDEV, BORDEV and FURDEV may differ, the principles are the same.

Table 4.1 shows the decision variables as either input or output, depending on the purpose of the calculations. We will be discussing these in detail in the next three chapters. Note, the field parameters are always input and the performance indicators are always output.

Table 4.1 The four calculation modes, with their main input and output variables

Mode	System parameters <sup>#</sup>	Decision variables		Performance indicators <sup>@</sup>	Remarks
		Input	Output		
1: Flow rate	I, n, $D_{req}$	L, $W^{1)}$	Q, $T_{co}$	$E_a$	$D_{min} = D_{req}$ ; $E_s = 1$
2: Dimensions	I, n, $D_{req}$	Q	L, $W^{1)}$ , $T_{co}$	$E_a$	$D_{min} = D_{req}$ ; $E_s = 1$
3: Cutoff time	I, n, $D_{req}$	L, $W^{1)}$ , Q	$T_{co}$	$E_a$	$D_{min} = D_{req}$ ; $E_s = 1$
4: Minimum depth	I, n, $D_{req}$	L, $W^{1)}$ , Q, $T_{co}$	—	$E_a$ , $E_s$ , DU	—

<sup>#</sup> Plus additional parameters for furrows and borders.

<sup>@</sup> Plus DU, SSR, and DPR (if applicable), and secondary output parameters.

<sup>1)</sup> The field width (W) applies to basins and borders only.

Before you can input data and start the calculations you need to select the mode you want by going to it with your cursor and pressing [Enter] or by typing its number and pressing [Enter].

### 4.3.2 Input windows and data entry

After you have selected your calculation mode, the screen will display two separate input windows (Figure 4.2). The window you will see on the left side of the screen is for specifying the field parameters. The window on the right side of the screen is for inputting the decision variables, which may number one, two, three or four, depending on the mode and the program. The philosophy behind these two separate input windows is that for a particular application you will usually only change the values under the heading *Input decision variables* in consecutive runs to improve the irrigation performance, while keeping the parameters under *the Field parameters* the same. To carry out sensitivity analyses, however, you will only need to change the values of the field parameters once you have obtained satisfactory results in Mode 3 or 4.

To change an input value, move your cursor to the data you wish to change, type in the new value and press [Enter] to confirm. If the programs do not accept the new value, a message with further instructions will appear. You can correct typing errors with [BackSp] or [DEL]. If you press [Enter] while inputting data, a message may appear stating that the input falls outside of the accepted range. Simply type another value. After you have entered all of the input, press [F2] (see bottom bar) to make a calculation.

FIELD PARAMETERS	INPUT DECISION VARIABLES
Intake family = 0.5 -	Flow rate = 50 l/s
Req. depth = 100 mm	Border length = 450 m
Flow resist. = 0.15	Border width = 20 m
Slope = 0.008 m/m	Cut-off time = 420 min

F2 Calculate | Edit input parameters for calculation mode 4 | BORDEV

Figure 4.2 The Bordev input screen

FIELD PARAMETERS		INPUT DECISION VARIABLES	
Required depth	= 100 mm	Flow rate	= 1 l/s
Max. velocity	= 13.8 m/min	Length	= 300 m
Flow resist.	= 0.04	Cut-off time	= 480 min
Slope	= 0.008 m/m		
Spacing	= 0.75 m		
Side slope	= 1 m/m		

FIELD PARAMETERS (INFILTRATION)	
Intake family	= 0.6

OUTPUT, Fixed flow, Mode 4	
Min. infilt. depth	= 90 mm
Applic. efficiency	= 77 %
Surf. run-off ratio	= 18 %
Deep perc. ratio	= 5 %
Storage efficiency	= 99 %
Distr. uniformity	= 86 %
Unif. coefficient	= 95 %

F3 Graph F4 Save PgDn = Next Window FURDEV

Figure 4.3 Input and output screen (Furdev)

### 4.3.3 Output and save

The results of the calculations will be shown in the lower right-hand window. Both the input and the output are displayed on the screen (Figure 4.3). Two function keys are active in this screen (see bottom bar). With [F3], you can also see the results graphically (Figure 4.4). If you want to save the graph,

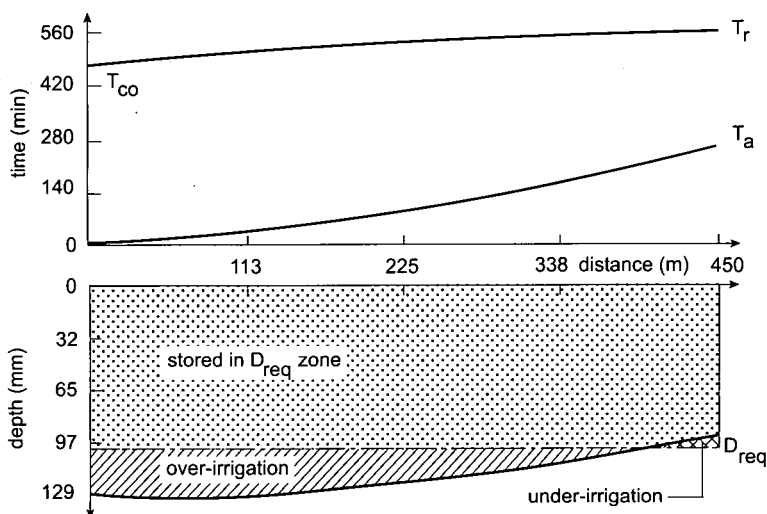


Figure 4.4 An output graph (Bordev)

FIELD PARAMETERS		INPUT DECISION VARIABLES	
SCS intake family		Flow rate	= 40 l/s
# = 1.0		Basin length	= 50 m
n = 0.15		Basin width	= 30 m
Dreq = 80 mm			

Save file as	
C:\SURDEV\BASDEV\TEST1	min
<input type="button" value="Append"/> <input type="button" value="Overwrite"/>	

Maximum infiltrated depth	= 98 mm
Average applied depth	= 91 mm
Application efficiency	= 88 %
Advance time	= 38 min
Recession time	= 152 min

Append last run to existing file		BASDEV
----------------------------------	--	--------

Figure 4.5 Saving a file

press either [F8] or [F9] (see bottom bar). The screen will then display a window asking you to give the graph a name. After you have done so, the programs will save the graph under this name with a “pcx” extension. (see also Section 4.4.2).

With [F4], you can save both the input and the output of the calculations. By pressing this key, the screen shows you a path (ie, drive and folder) and file name that you can confirm or change at will. When you make a calculation for the first time, the program will show you a default path and a default file name. The standard file names are “stanbas” for BASDEV, “stanbor” for BORDEV and “stanfur” for FURDEV. (Note, these are only names; the files will remain empty until you press [Enter]). You can change both the path and the file name by using the built-in editor. Note, you cannot enter the file name extension. SURDEV automatically adds default extension to the file names as follows: “bcr” for BASDEV, “scr” for BORDEV and “fcr” for FURDEV.

You must press [Enter] to actually save the file that contains all the input and output data and the graphs. Once you have changed the default path, this screen will display the new path as the default path when you run the program again. We designed the programs in this way because we expect that you will normally be working on the same study or project for some time, saving all of the relevant files in the same folder. If and when your work is interrupted from time to time, you can simply return to and continue to use this same folder.

The first time you press [F4] and then [Enter], the programs will save the file straightaway. When you press [F4] after a subsequent run, the Save window will display the choices *Overwrite* and *Append* (Figure 4.5). If you select

*Overwrite* (or if you press “o”) and then press [Enter], the programs will save the new file under the indicated name, thereby overwriting the contents of the old file. If you select *Append* (or if you press “a”) and then press [Enter], the programs will add the current results to the previous contents of the file you are working in. You can append 19 runs to one and the same file. Such a “track record” can be useful when you want to do several simulation runs to find an optimum result and to check which input combinations you have tested.

## 4.4 Files

*Files* is the first item on the main menu bar. The normal procedure for retrieving a file is to select the *Load* or *View/Print* option from this menu. The screen will then display a path. Press [Enter] again to see a list of the files that belong to the program you are using. Select the file by going to it with your cursor and pressing [Enter]. If the file you want to use is in another folder, press <Esc> and change the path. You can use [F6] to see for the list of existing folders on that path. To select a folder, go to it with your cursor and press [Enter].

### 4.4.1 Load

Use *Load* if you wish to resume work in an existing file. When you use *Load* to select a file, the programs automatically continue in the input screen of the *Calculation* menu, showing you only the input of the last run in that file. To continue working with these data, you will have to enter new input, press [F2] to perform the calculations of the run and append the results as we described in Section 4.3.3. Note, if you have changed the path under this option, the new path will be shown as the default path when you run the programs again. This feature also applies when you save a file with [F4].

### 4.4.2 View

*View/Print* displays the input and output data of a file, including all runs. When you use *View/Print* to select a file, you will see a screen like the one in Figure 4.6. The full path and file name will be displayed at the top of the screen. The first line of the screen shows the number of the run (1, 2, and so on). The second line shows in which calculation mode the run was made (Mode 1, Mode 2, and so on). In the left-hand column, you will see the input and output of the runs. Some variables can be either input or output, depending on the purpose of the calculation and the corresponding calculation mode. For this reason the program lists such variables in both categories (ie, in “input”



Run nr.		1	2	3	4	5	6
Calculation mode		2	3	4	4	4	4
-----							
INPUT PARAMETERS		units					
Flow rate	l/s	30	30	30	30	30	30
Basin length	m	-	30	30	30	30	30
Basin width	m	-	30	30	30	30	30
Cut-off time	min	-	-	45	40	35	30
Required depth	mm	80	80	80	80	80	80
Flow resistance	-	0.20	0.20	0.20	0.20	0.20	0.20
SCS #	-	1.5	1.5	1.5	1.5	1.5	1.5
Time rated T100	min	-	-	-	-	-	-
Inf. par. A	-	-	-	-	-	-	-
Inf. par. k	mm/min <sup>1/4</sup>	-	-	-	-	-	-
-----							
OUTPUT PARAMETERS							
Flow rate	l/s	-	-	-	-	-	-
Basin length	m	28	-	-	-	-	-
Basin width	m	28	-	-	-	-	-
Cut-off time	min	41	47	-	-	-	-
Applic. efficiency	%	88	86	89	96	100	100
Storage efficiency	%	-	-	100	96	88	75
-----							
F3 Graph F5 Print/Save F7 Delete run							

Figure 4.6 View screen with Files - View/Print

and "output"). If the variables are input, the value will show up in the upper part of the screen and "-" in the lower part. If they are output, they "-" will be in the upper part of the screen and the value in the lower part. The keys that you use to scroll through the data are slightly different in each of the three programs. The relevant keys are clearly indicated in the bottom bar.

If an error occurred when you made a run; and if you discovered this only after you saved the run, you can still delete it. Move your cursor to the run column that you want to delete and press [F7]. However, if there is only one run left, you cannot delete it.

To view the graph that belongs to a particular run, move your cursor to the run and press [F3]. If you want to print this graph, press [F8] or [F9] (see bottom bar). The screen will then display a window asking you to give the graph a name. After you have done so, the programs will save the graph under this name with a "pcx" extension in the same path as the file to which the graph belongs. You can then print the graph using any software package that has graphical capabilities.

#### 4.4.3 Print

You can print from the *View/Print* option. Once the file is displayed on the screen, press [F5] and then select *Printer*, *Text file*, or *Spreadsheet file*.

To print a file directly from the screen, select *Printer*. As long as the printer settings are correct, this option will produce a printout of what you see on the *View* screen. A message will appear on your screen if the printer is not con-

nected to your computer, or if it is not switched on, or if the printer specifications are incorrect. To check or change the printer location or the status of the computer's printer port, press [F10]. This will give you two options: *Local* and *Remote*. Select *Local* if your printer is connected directly to the port. If this is not the case (eg, if access to the printer goes through a network), select *Remote*. This will give you three further options for selecting the correct printer port (LPT). If you print through a network, you must know which port is the valid one. Note, as long as you do not change the printer settings, the programs will automatically use your last selection.

To edit file input and output (eg, for a report), select *Text file*. The programs will then save the file as a text file, automatically adding the extension "txt". If you retrieve such a file in a word-processing program, you can edit the format of the text and the data and use the print facilities of that program. Examples of editing are given in the last sections of Chapters 5, 6, and 7.

To save a file in a format that can be imported into a spreadsheet program, select *Spreadsheet file*. The programs will then save the file as a text file, automatically adding the extension "prn". If you retrieve such a file in a spreadsheet program, you can make graphs that show relationships between two parameters (see Chapter 8 for examples of some applications). Note, if the spreadsheet program asks you for more information, select "comma-delimited".

## 4.5 Units

*Units* is the second item on the main menu bar. In the *Units* sub-menu, you can select either metric units or imperial units for flow rate, length and depth, and either minutes or hours for time. The programs use the selected units throughout and save them with the results file. When you quit one of the programs, it will reset the changes that you made during the session to the default units. The default units for the programs are: litres per second for Q; metres for L and W; millimetres for D; and minutes for T. If you work in these units customarily, you can disregard this menu item.

The programs make the necessary conversions automatically throughout, consequently, you can use the programs to calculate conversions. For example, let us assume that you have selected  $\text{m}^3/\text{min}$  for the flow rate in the *Units* menu. Now go to the *Calculation* menu, Modes 2, 3 or 4, where flow rate is an input, and enter a certain value, say  $2.1 \text{ m}^3/\text{min}$ . Now go back to *Units* and select l/s for flow rate. Return to *Calculation* and select any Mode for which flow rate is an input. You will see a value of 35 l/s on the screen.

## 4.6 Miscellaneous

We have explained how you can change the drive, folder and file names in the three programs. It is not possible, however, to copy, move, delete or rename a file. If you want to do any of these things, you must exit SURDEV and use a common file manager.

If something goes wrong, the screen will display a red field with an error message. The error message tells the user not only what is wrong, but also what he can do about it. The programs display warning messages for DOS errors, input-range errors and calculation errors. Common DOS error messages include "Drive not ready", "File not found" and "Printer not attached". The other two types of error messages are specific to BASDEV, BORDEV and FURDEV, which we will deal with in more detail in Chapters 5, 6 and 7.



## 5 BASDEV user manual

BASDEV is a modular, menu-driven computer program developed to solve problems in the design, operation and evaluation of level basin irrigation systems. You start the module by selecting it in the SURDEV package. The installation procedure of this package was discussed in Chapter 4, Section 1.

### 5.1 Menu structure

There are five main menu items, four of which have sub-menus that you can select by moving the highlight with the arrow keys and pressing [Enter], or by typing the red (bold) character. Table 5.1 shows the structure of the main menu and its first layer of sub-menus.

#### 5.1.1 Sub-menu files

In the sub-menu *Files*, there are two options: *Load* and *View/Print*. With *Load*, you can select an existing file and continue with the calculations. With *View/Print* you can select an existing file, the contents of which will be displayed on the screen. Pressing [F5] gives you the option to print this file or to save it as a text file or spreadsheet file. For more information on these topics, see Chapter 4, Section 4.3.

#### 5.1.2 Sub-menu units

The sub-menu *Units* gives you a choice of units for flow rate, length, depth and time, which include:

- Flow rate: litres per second, cubic metres per minute, cubic feet per second, or US gallons per minute.
- Length: metres or feet. These are used for basin length and width.

Table 5.1 Basdev menu structure

Files	Units	Infiltration	Calculation	Quit
Load	Flow rate	Modified SCS families	1. Flow rate	
View/Print	Length	Time-rated families	2. Dimensions	
	Depth	Kostiakov equation	3. Cutoff time	
	Time		4. Min. Depth	

- Depth: millimetres, centimetres, or inches. These are used for the various supplied and infiltrated depths.
- Time: minutes or hours. These are used not only for advance, cutoff, depletion and recession time, but also for the infiltration equations.

The selected units are maintained throughout the program and are also saved with the file. When the program is started, default units are litres per second for flow rate, metres for basin dimensions, millimetres for infiltrated depths and minutes for time.

### 5.1.3 Sub-menu infiltration

In the sub-menu *Infiltration*, you can select one of three infiltration input modes (Table 5.1). All the modes are based on the infiltration characteristics of a soil as described by the Kostikov equation (Equation 3.1)

$$D_i = kT^A$$

where  $D_i$  is the cumulative infiltration after an infiltration opportunity time  $T$ ,  $A$  is the infiltration exponent and  $k$  is the infiltration constant.

In BASDEV, you can enter the soil infiltration characteristics  $A$  and  $k$  indirectly by using the Modified SCS Intake Families and the Time-Rated Families, or directly by giving values to  $A$  and  $k$ . For more background information on this subject, the reader is referred to Chapter 3, Section 1.1. The default infiltration input mode is the *Modified SCS family*.

### 5.1.4 Sub-menu calculation

The sub-menu *Calculation* is the only place in BASDEV where the input data can be entered but, before doing this, you need to select one of four different calculation modes (Table 5.1). What the first three modes have in common is that the calculated minimum infiltrated depth at the downstream end of the basin always equals the required depth. In other words, no under-irrigation will occur and there will always be over-irrigation in the upstream part. When to use the various modes is summarised below:

#### *Calculation Mode 1: Flow rate*

Calculation Mode 1 is primarily for design purposes when the dimensions of the basin are known and you want to know the approximate flow rate that is needed to achieve a reasonable performance. The program will also give you

the required cutoff time and the primary performance indicators as well as various depth and time parameters.

We emphasise that Mode 1 does not give a "best solution". It only serves as a "first shot" at a reasonable application efficiency. Depending on the type of soil and the required depth, the resulting efficiency in this mode varies between 70 and 95 per cent. This efficiency can be increased in Calculation Mode 3 (eg, by increasing the flow rate). If an inexperienced user were to start straightaway with Mode 3, he may inappropriately select values of input variables that give a poor performance or even error messages. Starting with Mode 1 avoids too many trials or error messages.

#### *Calculation Mode 2: Dimensions*

Calculation Mode 2 is the reverse of Calculation Mode 1: the flow rate is now known and you want to know the approximate basin dimensions that are needed to achieve a reasonable performance. The program will also give you the required cutoff time, together with the primary performance indicators and infiltrated depths. BASDEV uses a standard length/width ratio of 1 (ie, square basins) for the calculation of the basin dimensions.

The resulting application efficiency is similar to that in Mode 1. Here again, the calculated values for basin dimensions and cutoff time are only a "first shot". In Mode 3, you can change the size and shape of the basin to try to increase the application efficiency (eg, by decreasing the basin dimensions).

#### *Calculation Mode 3: Cutoff time*

Calculation Mode 3 is one of the two main modes of BASDEV. It will be the most frequently used and is the starting mode for the experienced user. Here, both the flow rate and basin dimensions are input. The required cutoff time is the resulting decision variable, while also the primary performance indicators and depth and time parameters are given. The calculated cutoff time is such that the minimum infiltrated depth is equal to the required depth. This mode is suitable for a quick try out of the various options for design and operation.

#### *Calculation Mode 4: Minimum depth*

In Calculation Mode 4, the other main mode, the cutoff time is specified as input in addition to the basin dimensions and the flow rate. Thus, all design variables are input, which means that the required depth at the end of the field will usually not be achieved, and under and/or over-irrigation will occur. The main indicator is the minimum infiltrated depth, occurring at the far end of the field. It is therefore given as the first output parameter, followed by the primary performance indicators and infiltrated depths. This mode is most suitable for a performance evaluation of an existing level basin irrigation system and for testing the performance sensitivity to a change in the field parameters. Together, Modes 3 and 4 constitute the core of BASDEV.

## 5.2 Input windows

When a calculation mode has been selected, BASDEV will display two windows on your screen for data entry: *Field Parameters* and *Input Decision Variables*. The input data to be provided in the two windows are summarised in Table 5.2. Usually, you will only need to change the values of the field parameters to carry out sensitivity analyses after you have obtained satisfactory results in Mode 3 or 4 (see Chapter 4, Section 3.2). Calculation examples can be found in Chapter 8, Section 1.1.

### 5.2.1 Field parameters

#### *Infiltration*

Upon selection of the *Modified SCS families* type of infiltration data, BASDEV will use the intake families as discussed in Chapter 3, Section 1.1. One of the eight families can be chosen. If a wrong number is typed, an error message with a list of acceptable numbers is shown. Instead of typing a number, you can also use the help screen by pressing [F1] while keeping the cursor on the family number. A screen with family numbers will then pop up from which you can make your selection. The same screen also shows the corresponding approximate soil types, as shown in Figure 5.1.

When a family number has been selected, the corresponding values for Kostiakov's A and k are used internally by the program (see Table 3.2). You can check this by selecting a family number, going back to the sub-module *Infiltration type*, selecting Kostiakov mode, and returning to the input window again, which then shows the corresponding A and k values.

If you select *Time-Rated Families*, you must specify the time required to infiltrate 100 mm ( $T_{100}$  in the Field Parameters window). Although originally seven time-rated intake families were presented (see Table 3.4), the program

Table 5.2 Input variables for the Basdev calculation modes

Input variables	Mode 1	Mode 2	Mode 3	Mode 4
Field Parameters				
Infiltration	o	o	o	o
Flow resistance, n	o	o	o	o
Required depth, $D_{req}$	o	o	o	o
Input Decision Variables				
Length, L	o		o	o
Width, W	o		o	o
Flow rate, Q		o	o	o
Cutoff time, $T_{co}$				o



FIELD PARAMETERS	INPUT DECISION VARIABLES
SCS intake family # = <b>1.0</b> n = 0.15 Dreq = 80 mm	Flow rate = 40 m <sup>3</sup> /s Basin length = 50 m Basin width = 30 m

S.C.S. Intake families	
Family #	Soil classes
0.1	clay, silty clay
0.3	silty clay, clay loam
0.5	clay loam, loam
<b>1.0</b>	loam, silt loam
1.5	silt, sandy loam
2.0	sandy loam, fine sand
3.0	fine to medium sand
4.0	medium to coarse sand

Select intake family
BASDEV

Figure 5.1 Selecting an intake family

accepts any value ranging between 10 and 2000 minutes. If you assign a value for  $T_{100}$ , BASDEV will internally use the corresponding values for Kostiakov's A and k. You can check this by following the same procedure as outlined above for the modified intake families.

If the *Kostiakov equation* is selected, the exponent A and the coefficient k must be specified. Under the Help key, [F1], you will find a table with A and k values corresponding (approximately) to various soil types.

Conversion of A and k values for other than the default units can be done as follows: go back to the *Units* menu; change time and depth units, and return to the *Field Parameters* window, where the new values with their modified units will appear.

#### *Flow resistance*

The value of Manning's roughness coefficient, n, can be specified in the *Field Parameters* window. Accepted values range between 0.01 and 0.50. For practical purposes, however, values given in Table 3.5 are recommended. This table is also available under the Help key, [F1], when the cursor is on the n-value.

#### *Required depth*

The required depth to be infiltrated at the end of the basin is given as the last input in the *Field Parameters* window. This target is determined outside BASDEV, as indicated in Chapter 3, Section 1.3. The accepted range is between 40 and 500 mm.

### 5.2.2 Decision variables

The decision variables in surface irrigation are normally the field dimensions (length and width), flow rate and cutoff time. Which of these parameters appear under the heading *Input Decision Variables* depends on the selected calculation mode (see Table 5.2).

#### *Basin dimensions*

You can prescribe values for the basin length and width in Calculation Modes 1, 3 and 4. In Mode 3, increasing the length will lower the performance, because the advance time with the given flow rate will be longer. Applying a larger flow will then enable a greater length. In Mode 4, when using the program for evaluation purposes, you either prescribe the basin dimensions of an existing situation or you keep them as determined in Mode 3.

#### *Flow rate*

Flow rate values can be given in Calculation Modes 2, 3 and 4. Decreasing the flow rate too much would result in the flow not reaching the end of the field. Contrarily, there is also a practical upper limit, above which the performance will hardly improve (see Chapter 8, Section 1.1). In Mode 4 you either keep the flow rate as determined in Mode 3 or, when using BASDEV for evaluating an existing situation, take the value from the field.

#### *Cutoff time*

Values for the cutoff time can only be given in Calculation Mode 4; there are, however, practical limitations to changing its value. When you go to Mode 4 after having run Mode 3, the displayed cutoff time corresponds to a situation where the minimum infiltrated depth at the downstream end of the basin matches the required depth. Increasing the cutoff time will result in over-irrigation and a lower application efficiency. On the other hand, if you decrease the cutoff time of Mode 3 in Mode 4, you will introduce under-irrigation, yielding a higher application efficiency but a storage efficiency becoming lower than 1.

The cutoff time should not be much shorter than the advance time calculated for the same input combination. This would give an unacceptably poor result or even an error message, because insufficient water will reach the end of the field, or no water at all.

### 5.2.3 Input ranges

As shown in Table 5.3, ranges have been fixed for all input variables and are in metric units. If other units are chosen in the menu, the indicated ranges are converted in the program.

Table 5.3 Accepted ranges of input parameters

Input parameters	Accepted values
<b>Field Parameters</b>	
SCS family #	0.2 - 4.0
Time-rated T	10 - 2000 min
Infiltration coefficient k	0.8 - 45.0 mm/min <sup>A</sup>
Infiltration exponent A	0.2 - 1.0
Flow resistance, n	0.01 - 1.00
Required depth, D <sub>req</sub>	40 - 500 mm
<b>Input Decision Variables</b>	
Basin length, L	5 - 800 m
Basin width, W	5 - 500 m
Flow rate, Q	5 - 600 l/s
Cutoff time, T <sub>co</sub>	10 - 800 min

Fixing of the ranges based on a large number of runs has been done to avoid too many impossible combinations and corresponding error messages. For all practical purposes, the indicated ranges of the individual parameters will be more than sufficient. If you combine extreme values of the various parameters, you may not get a result. In that case, BASDEV will flash you a message on the screen indicating how to change these values in order to get a result.

The above ranges are ignored for output results, so, no warning will be given if an out-of-range value obtained is subsequently used as input in another mode.

### 5.3 Output window

Once all input has been entered, press [F2] for the calculation and output. The screen again shows the two input windows, but a third window has now been added showing the results (Figure 5.2). These are depicted in various groups, separated by a blank line.

The first group contains the desired decision variables, according to the selected calculation mode. In Mode 1 they are the flow rate and the cutoff time, in Mode 2 the basin dimensions and the cutoff time, in Mode 3 it is the cutoff time, and in Mode 4 it is the minimum infiltrated depth.

The second group contains the primary performance indicators as discussed in Chapter 3, Section 3. In Modes 1, 2 and 3, this is the application efficiency (with the maximum and average infiltrated depths); in Mode 4 the storage efficiency and the distribution uniformity are added.

Finally, there is a group with various time parameters. The output results for the various modes are listed in Table 5.4. Note, the distribution uniformity (DU) is not given in Modes 1, 2 and 3, because, it equals the application efficiency for basin irrigation, as long as the required depth is achieved (which

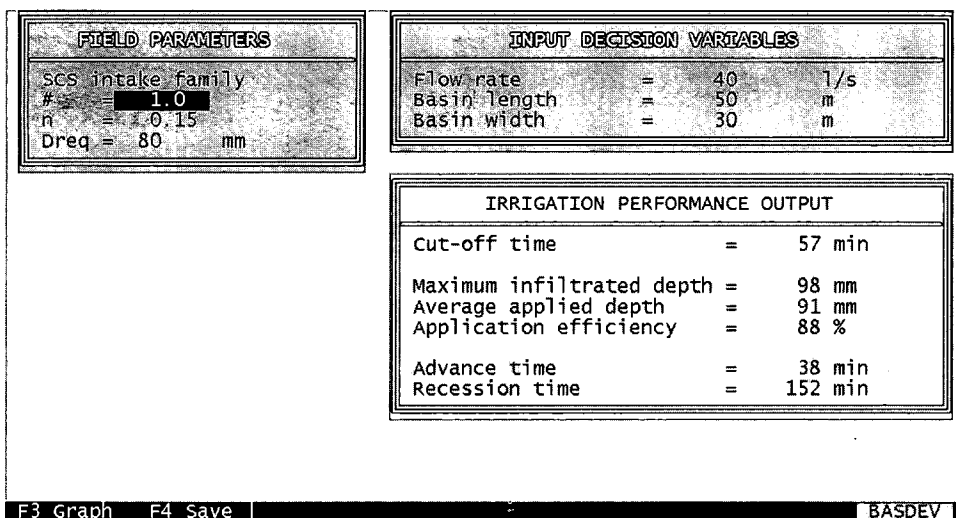


Figure 5.2 Performance output for Basdev

the program ensures). In Mode 4, the application efficiency and the distribution uniformity are usually not the same and hence both are shown.

The key [F3] shows you two graphs with the main results: the upper one shows the cutoff time and the advance time in relation to field distance, and

Table 5.4 Output results for the Basdev calculation modes

Output parameters	Mode 1	Mode 2	Mode 3	Mode 4
<b>Design variables</b>				
Basin length		o		
Basin width		o		
Flow rate	o			
Cutoff time	o	o	o	
<b>Primary performance indicators</b>				
Application efficiency	o	o	o	o
Distribution uniformity				o
Storage efficiency				o
<b>Infiltrated depths</b>				
Minimum infiltrated depth	o	o	o	o
Maximum infiltrated depth	o	o	o	o
Average applied depth	o	o	o	o
Under-irrigation (length/depth)				o
Over-irrigation (length/depth)				o
<b>Time variables</b>				
Advance time	o	o	o	o
Recession time	o	o	o	o

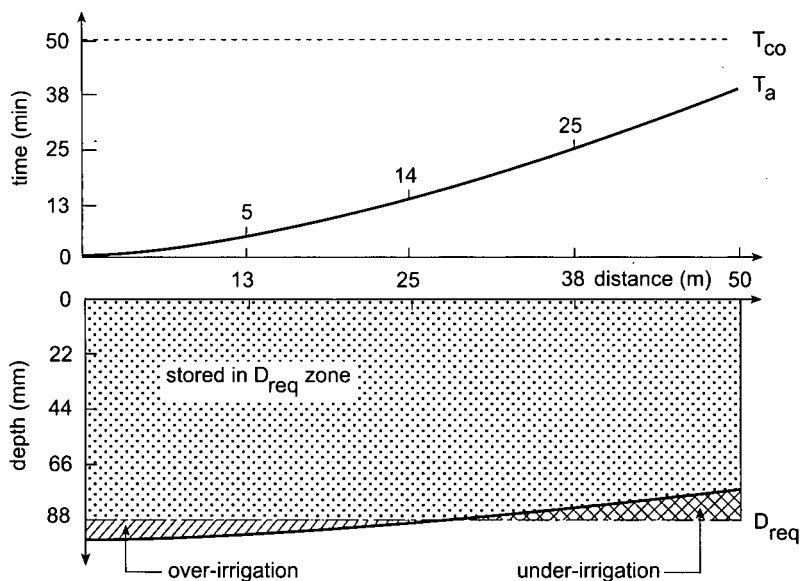


Figure 5.3 Graphic output of advance curve and infiltration profile

the lower one shows the infiltrated depths along the length of the field. Where applicable, under and over-irrigation are indicated. The graph can be saved if you press [F8] or [F9], depending on whether you want to print it in colour or in black-and-white. Figure 5.3 shows a graph that was made by running BASDEV in Mode 4 with default values, except for the cutoff time, which was taken as 50 minutes.

You can save the tabulated simulation results together with the input data by pressing [F4]. In a small window, the path (folder + file name) can be confirmed or changed, as described in Chapter 4, Section 3.3. You can overwrite the previous file or append the current results to it. Further processing of the saved results file must be done under the *Files* menu, using *View/Print* (see Chapter 4, Section 4).

## 5.4 Error messages

When you start with Mode 1 or 2 to get proper initial estimates, BASDEV will usually give an output as a result of the calculations. Yet, particularly when working in Modes 3 and 4, BASDEV may flash you error messages on the screen. Such an error message will usually start with

### **Change one or more input parameters**

and be followed by suggestions on which parameter to decrease or increase.

The suggestion will depend on the mode and on the input value. Possible problems can be grouped into three categories (ie, computational problems, physical problems, and cutoff time problems).

#### *Computational problems*

In the calculation algorithm of BASDEV, the parameters are scaled to facilitate a solution to the equations. It is impossible to do this in such a way so that all combinations of all parameters can be solved. As a result, a calculation problem may occur with some combinations of extreme values of parameters, although the input ranges given in Section 5.2.3 have been fixed so as to avoid too many problems. Note, a problem such as this is always related to a (virtual) poor irrigation performance: an unacceptably low application efficiency or excessive under-irrigation. This will not happen if you use a combination of input parameters that will result in the performance you will normally try to achieve.

#### *Physical problems*

The combination of input values could be such that it is physically impossible to get a result. This can happen, for instance, with small flows on large basins, or with very light soils and large basins. In these cases, Modes 1, 2, and 3 will flash you a message on the screen because the required depth cannot be realised, or in Mode 4 when the flow will not reach the end of the basin at all. This is not a calculation problem, but a signal that it is physically impossible to get a result with the given set of input values.

#### *Cutoff time problem*

The calculation algorithm and the solution procedures of BASDEV cannot handle a cutoff time that is substantially shorter than the advance time. For instance, a high flow rate in a short basin will give a short advance time, but because of the high flow rate, the cutoff time (being the required volume divided by the flow rate) may be even less. The same problem could occur if the specified cutoff time in Mode 4 is too short. No single remedy can be given to circumvent this problem, and suggestions on the screen therefore vary with the calculation mode.

As long as the flow is cut off when advance has passed 90 % of the basin length, the program will give a result. With cutoff when advance is between 90 and 100 % of the field length, computation results will be somewhat inaccurate, but they will be acceptable for practical purposes.

Many runs with BASDEV have shown that the occurrence of this type of problem gives inadequate results anyhow. You can verify this by generating such an error message in Mode 3 or 4, and then gradually changing one of the input values as recommended by the message. This will lead to a rather poor first result: too much under-irrigation in Mode 4, or a very low application efficiency in Mode 3.

## 5.5 Assumptions and limitations

The BASDEV program is based on a model that is assumed to represent the process of basin irrigation. This model (described in detail in Appendix A) involves assumptions on the validity and accuracy of the algorithm used, and also on the procedures to solve the equations. The use of BASDEV is thus limited to conditions where these assumptions are valid. In addition, the model itself is a schematisation that includes a number of practical assumptions on conditions that require fulfilment. These may also restrict the use of BASDEV. We therefore briefly discuss the theoretical assumptions and the practical limitations of the use of BASDEV for design, operation, or evaluation of a level-basin surface irrigation system. As explained in Appendix A, the model assumes that:

- The modified Eulerian cell approach with the modified zero-inertia model is appropriate for simulating the advance phase.
- The modified Manning equation and flow resistance coefficients are sufficiently accurate in describing the surface flow component.
- The infiltration characteristics and the approximation of infiltration profiles are sufficiently accurate in describing the infiltration component.
- The numerical solution procedures are sufficiently accurate in establishing the volume balances.
- The simplifications of storage and recession phase are realistic.

Apart from these more theoretical assumptions related to the algorithm and its solutions (ie, accepting the model as it is), there are a number of practical conditions that should be fulfilled. The most important are the following:

- There is no surface runoff. This is a reasonable assumption, which is achieved by ensuring that the bunds all around the basin are sufficiently high and by working with reasonable water depths.
- Inflow is evenly distributed over the width. The program works with unit flows, whereby the total inflow is divided by the basin width. This allows a two-dimensional calculation of the surface flow on a one-metre-wide strip (surface flow in length direction and infiltration in vertical direction). Slight variations (eg, when inflow is distributed over the width by an adequate number of siphons) will not produce a severe limitation on longer fields, because flow from the siphons will rapidly spread out to form one straight front. If water is supplied from one inlet point, however, a head ditch can be made to make basin inflow more uniform. For situations with a point inlet, Clemmens et al. (1995) state that for length-width ratios of  $>2$ , the location of the inlet has no effect on advance. For basins that are almost square, they recommend using the diagonal distance as the field length, and using a calculation width that is the actual basin area divided by the diagonal distance.
- Inflow is constant during the supply period. A deliberate inflow cutback is

not needed with basin irrigation, because there is no surface runoff. In practice, fluctuations in flow rate may occur. Minor fluctuations around the intended value will not be a problem, because their effect is levelled out during advance, especially if cutoff occurs later than advance time. Reddy and Clyma (1982) showed that this also applies to larger variations. The influence of systematically lower or higher inflows can be assessed with BASDEV itself.

- Infiltration and flow resistance are uniform over the basin area. Substantial variations in infiltration will certainly affect the performance, but to what extent this occurs depends on the values of the other parameters. Variations in flow resistance usually have less influence. Resistance that is generally higher than assumed will result in the advance time being later, consequently, performance will be poorer. Calculations of design and performance sensitivities can indicate the accuracy required in these inputs.
- The basin surface is level in all directions. A slight gradient lengthways is acceptable (eg, up to half the maximum flow depth), the calculations thereof need not be adjusted because the advance will be faster and the practical result would be a slightly better performance than calculated. Slopes across the field, however, should always be avoided. Undulations (high and low spots) seriously affect the performance, because the surface flow first has to fill the low spots before it can overcome the higher spots. This can be avoided by proper levelling. Deviations of about 15 mm, as achieved with laser-controlled levelling, have little effect, but deviations of more than 40 mm are not acceptable (Dedrick et al. 1982).

Finally, we must emphasise that BASDEV only deals with the technical-hydraulic aspects of basin irrigation. In a proper design or operation, the program result only constitutes one element of the total considerations, which should also include topographic, agricultural, economic, and social aspects. In addition, one should take into account the relationships between field irrigation, the water distribution in the tertiary unit and the supply regimes in the main system. Therefore, an overriding assumption of BASDEV is that the user is fully aware of its limitations and must give due consideration to all these other aspects as well.

## 5.6 Program usage

The following eight steps are important in the usage of the BASDEV program.

1. Start the SURDEV package. Select BASDEV from the main menu of SURDEV.
2. If you want to use an existing file, retrieve it with the *Load* command under the *Files* menu. If you want to make a completely new file, go



straight to the *Calculation* menu bypassing the *Files* menu and you will get the default data.

3. If you normally work with the default unit settings, you can skip the *Units* menu. Select *Units* only if you want to work with other units.
4. Specify which type of infiltration characteristics you will be inputting in the *Infiltration* menu. The program default is the Modified SCS families infiltration type.
5. Go to the *Calculation* menu and select a mode to work in. Most of the work will be done in Modes 3 and/or 4. Less experienced users can start in Mode 1 or 2 to get a first estimate of flow rate or field dimensions, respectively. Mode 4 can be used to evaluate an existing situation or to do sensitivity analyses,
6. In the input window, you can specify field parameters and decision variables, after which you can run the program with [F2].
7. You can view the results of each run in tabular form in the output window, or in graphical form with [F3]. The results of one simulation run (output and input in one file) can be saved in a separate file or can be appended to earlier runs in an existing file with [F4].
8. Select *Files* and *View/Print* from the main menu to see what has been done and/or to print a file directly, or convert it to a print file for a word-processor program, or convert it to a file that can be imported into a spreadsheet program where you can carry out further analyses and make your own graphs.

## 5.7 Sample problems

In most cases, the user will not be satisfied with a solution obtained after one run, and he will usually do a number of runs to get an acceptable solution. Two simple examples are given to illustrate this procedure. For more elaborate problems, see Chapter 8, Section 1.

### 5.7.1 Determine basin dimensions

A design is to be made for a situation where the available flow rate is fixed at 30 l/s. The soil type is sandy loam and can be classified with the Modified SCS family #1.5 (Table 3.2). The net irrigation requirement is 80 mm. The crops are grown in rows in the direction of flow, so the value of the flow resistance can be taken as 0.20 (Table 3.6). Determine the basin dimensions in such a way that the application efficiency is at least 80 per cent and the cutoff time has a practical value. The maximum possible basin length is 30 m.

1. We want to make a new file, and therefore need not use the *Files* sub-

menu. Observe that the default units and infiltration modes are to be used in this problem, so you can go directly to the *Calculation* menu and select Mode 2: Dimensions. Enter the above values in the two input windows and make a run ([F2]).

2. The results of this run (Table 5.5, Run 1) show that with an available flow rate of 30 l/s a square field of 28 by 28 m can be irrigated with an application efficiency of 88 per cent. This is sufficiently high, but the basin length is less than the maximum. Go to Mode 3 to see the effect when the basin dimensions are increased to 30 by 30 m.
3. The results of this run (Table 5.5, Run 2) show that the slightly larger basin causes a reduction in the application efficiency from 88 to 86 per cent, which is still acceptable. The cutoff time, however, has an impractical value. Therefore, we now go to Mode 4 to see the effect when the cutoff time is reduced from 47 to 45 minutes.

Table 5.5 Basdev program for level basin irrigation (Filename: EXAMPLE1)

Run no.		1	2	3
Calculation Mode		2	3	4
<hr/>				
Input parameters	Units			
Flow rate	l/s	30	30	30
Basin length	m	—	30	30
Basin width	m	—	30	30
Cutoff time	min	—	—	45
Required depth	mm	80	80	80
Flow resistance	—	0.20	0.20	0.20
SCS #	—	1.5	1.5	1.5
Time rated T	min	—	—	—
Inf. par. A	—	—	—	—
Inf. par. K	mm/min^A	—	—	—
<hr/>				
Output parameters				
Flow rate	l/s	—	—	—
Basin length	m	28	—	—
Basin width	m	28	—	—
Cutoff time	min	41	47	—
Applic. Efficiency	%	88	86	89
Storage efficiency	%	—	—	100
Distribution unif.	%	—	—	85
<hr/>				
Min. inf. Depth	mm	—	—	77
Max. inf. Depth	mm	98	101	98
Average depth	mm	91	93	90
Over-irr. Depth	mm	—	—	11
Under-irr. Depth	mm	—	—	2
Over-irr. Length	m	—	—	27
Under-irr. Length	m	—	—	3
Advance time	min	25	30	30
Recession time	min	102	106	102

4. The results of this run (Table 5.5, Run 3) show that the reduction in cutoff time results in a slight under-irrigation: the minimum infiltrated depth is now 77 mm instead of 80 mm, but the storage efficiency is still 100 per cent (see also the graph, [F4]). Furthermore, the advance time is 30 minutes, so cutoff can be done 15 minutes after advance. The application efficiency has increased to 89 per cent and the distribution uniformity is 85 per cent. These results are acceptable.

Table 5.5 can be made with BASDEV. The procedure is as follows. Save Run 1 with [F4] and specify a file name (EXAMPLE1). BASDEV automatically adds the extension BCR to this file name. Save Runs 2 and 3 with [F4] under the same file name, using the Append option. Go back to the main menu, go to *Files* menu, select *View*. See the results and select [F5] (*Print/Save*) and then use the option *Text File*. BASDEV now automatically adds the extension TXT to the file name EXAMPLE1. If you now exit BASDEV, you can load the results in a word-processing program by retrieving the file EXAMPLE1.TXT. This is how you make Table 5.5.

### 5.7.2 Determine flow rate

A design is to be made for an existing basin of 100 by 80 m. From infiltrometer tests, the parameters of the Kostikov equation were determined as  $A = 0.68$  and  $k = 2.27 \text{ mm/min}^A$ . The net irrigation requirement is 100 mm. The flow resistance (broadcast small grains) can be taken as 0.15. Determine the flow rate in such a way that the application efficiency is at least 80 per cent and the cutoff time is not more than 3 hours.

1. Go to the *Infiltration* menu and select the Kostikov equation. Go to the *Calculation* menu and select Mode 1: Flow rate. Enter the above values in the two input windows and make a run.
2. The results of this run (Table 5.6, Run 1) show that this basin can be irrigated with an application efficiency of 83 per cent, given a flow rate of 80 l/s. A cutoff time of 201 minutes will then be required, implying that the cutoff time needs to be reduced. Run BASDEV in Mode 4 to see the effect when the cutoff time is reduced from 201 to 180 minutes.
3. The results of this run (Table 5.6, Run 2) show that although the application efficiency increased to 91 per cent, there is under-irrigation: the minimum infiltrated depth is 86 mm instead of the required 100 mm. Run BASDEV again in Mode 4 to see the effect when the flow rate is increased from 80 to 90 l/s.
4. The results of this run (Table 5.6, Run 3) show that there is now a slight over-irrigation: the minimum infiltrated depth is 104 mm and the application efficiency is reduced to 82. So, there is scope for reducing the flow rate

Table 5.6 Basdev program for level basin irrigation (Filename: EXAMPLE2)

Run no.		1	2	3	4
Calculation Mode		1	2	3	4
Input parameters	Units				
Flow rate	l/s	—	80	90	85
Basin length	m	100	100	100	100
Basin width	m	80	80	80	80
Cutoff time	min	—	180	180	180
Required depth	mm	100	100	100	100
Flow resistance	—	0.15	0.15	0.15	0.15
SCS #	—	—	—	—	—
Time rated T	min	—	—	—	—
Inf. par. A	—	0.68	0.68	0.68	0.68
Inf. par. k	mm/min^A	2.27	2.27	2.27	2.27
Output parameters					
Flow rate	l/s	80	—	—	—
Basin length	m	—	—	—	—
Basin width	m	—	—	—	—
Cutoff time	min	201	—	—	—
Applic. efficiency	%	83	91	82	87
Storage efficiency	%	—	98	100	100
Distribution unif.	%	—	80	86	83
Min. inf. depth	mm	—	86	104	95
Max. inf. depth	mm	133	121	132	126
Average depth	mm	121	108	122	115
Over-irr. depth	mm	—	13	22	16
Under-irr. depth	mm	—	7	0	2
Over-irr. length	m	—	75	100	91
Under-irr. length	m	—	25	0	9
Advance time	min	135	135	117	125
Recession time	min	397	345	394	369

somewhat. Run Mode 4 again to see the effect when the flow rate is decreased from 90 to 85 l/s.

5. This run (Table 5.6, Run 4) shows that the under-irrigation is negligible: the minimum infiltrated depth is 95 mm and the storage efficiency is still 100 per cent. The application efficiency is good (87 per cent). These results are acceptable.

Table 5.6 was also made with BASDEV as outlined above. Once you are familiar with the foregoing basic elements of working with the program, you can solve the more elaborate problems presented in Chapter 8. These concern several sets of runs with which various relationships can be established. They illustrate the further possibilities of BASDEV as well as providing a deeper insight into the complex nature of the basin irrigation process.

# 6 BORDEV user manual

BORDEV is a modular, menu-driven computer program developed to solve problems in the design, operation, and evaluation of sloping border irrigation systems. You start the module BORDEV by selecting it in the SURDEV package. The installation procedure of this package was discussed in Chapter 4, Section 1.

## 6.1 Menu structure

There are six main menu items, five of which have sub-menus that you can select by moving the highlight with the arrow keys and pressing [Enter], or by typing the red (bold) character. Table 6.1 shows the structure of the main menu and its first layer of sub-menus.

### 6.1.1 Sub-menu files

The sub-menu *Files* gives you two options: *Load* and *View/Print*. With *Load*, you can select an existing file and continue with the calculations. With *View/Print* you can select an existing file, the contents of which will subsequently be displayed on the screen. Pressing [F5] gives you the option of sending the contents of this file to a printer, a text file, or a spreadsheet file. For more information on these topics, see Chapter 4, Section 4.3.

### 6.1.2 Sub-menu operation

In the sub-menu *Operation*, you can select the appropriate system operation mode. If you select *Fixed flow* it means that a constant inlet flow rate will be used to irrigate the borders during the entire application time. Selecting *Cutback flow* means that, at the end of advance, the inflow is reduced for the remainder of the application time. Selecting *Tailwater reuse* refers to a border

Table 6.1 Bordev menu structure

Files	Operation	Units	Infiltration	Calculation	Quit
Load	Fixed flow	Flow rate	Modified SCS families	1. Flow rate	
View/Print	Cutback flow	Length	Kostiakov-Lewis equation	2. Length	
	Tailwater reuse	Depth		3. Cutoff time	
		Time		4. Min. Depth	

irrigation system with a runoff reuse arrangement. Because BORDEV only simulates the flow in one border, the reuse component is not integrated in the required flow rate of another border. The default operation mode is *Fixed flow*.

### 6.1.3 Sub-menu units

The sub-menu *Units* is where you can choose pre-determined units for flow rate, length, depth and time. The following units are available:

- Flow rate: Litres per second, US gallons per minute, cubic metres per minute, or cubic feet per minute.
- Length: Metres or feet, used for border length and width.
- Depth: Millimetres or inches, used for the various supplied and infiltrated depths.
- Time: Minutes or hours, used not only for advance, cutoff, depletion and recession time, but also for the infiltration equations.

The selected units are maintained throughout the program and are also saved with the file. When the program is started, default units are: litres per second for flow rate; metres for border dimensions; millimetres for infiltrated depths; and minutes for time.

### 6.1.4 Sub-menu infiltration

In the sub-menu *Infiltration*, you can select one of two different infiltration input modes. Both modes are based on the infiltration characteristics of a soil as described by the Kostiakov-Lewis equation (Equation 3.4):

$$D_i = kT^A + f_0T$$

where  $D_i$  is the cumulative infiltration after an infiltration opportunity time  $T$ ,  $k$  is the infiltration constant,  $A$  is the infiltration exponent, and  $f_0$  is the basic infiltration rate. In BORDEV, you can enter the soil infiltration characteristics  $A$ ,  $k$ , and  $f_0$  directly or indirectly by using the modified SCS families. For more background information on this subject, see Chapter 3, Section 1.1. The default infiltration input mode is the *Modified SCS families*.

### 6.1.5 Sub-menu calculation

Before actual data can be entered and calculations can be made, you have to select one of the four modes in the sub-menu *Calculation* (Table 6.1). What the first three modes have in common is that the calculated minimum infiltrated

depth at the downstream end of the border always equals the required depth. In other words, no under-irrigation will occur at the downstream end, whereas over-irrigation always occurs in the upstream part. When to use the various modes is summarised below.

#### *Calculation Mode 1: Flow rate*

Calculation Mode 1 is primarily for design purposes, when you know the border dimensions and want to know the approximate flow rate that is needed to achieve a reasonable performance. The program will also give you the required cutoff time and the primary performance indicators as well as various depth and time parameters.

For the operation modes *Fixed flow* and *Tailwater reuse*, BORDEV calculates the flow rate in such a way that the application efficiency is approximately maximised. For the operation mode *Cutback flow*, the flow rate is determined so that the user-specified advance ratio is achieved. Although the result obtained in this mode is usually close to these targets, it is nevertheless required that you continue running in Modes 3 and/or 4, because in most cases small refinements are still possible.

#### *Calculation Mode 2: Dimensions*

Calculation Mode 2 is the reverse of Calculation Mode 1: the flow rate is now known and you want to know the approximate border dimensions that are needed to achieve a reasonable performance. The program will also give you the required cutoff time and the primary performance indicators as well as various depth and time parameters. In this Mode, the user is required to give the length/width ratio a figure. The maximum application efficiency is approximate and to get a final result you must continue in Modes 3 and/or 4.

#### *Calculation Mode 3: Cutoff time*

Calculation Mode 3 is one of the two main modes of BORDEV. It will be the one most frequently used and will also be the starting mode for the experienced user. Here, both the flow rate and border dimensions are input. The required cutoff time is the resulting design variable, while the application efficiency and other secondary output are also given. Note, in this mode, the advance ratio is an output, because it is not possible to fix advance ratio, border dimensions and flow rate and, at the same time, satisfy the requirement that the minimum infiltrated depth equals the required depth.

#### *Calculation Mode 4: Minimum Depth*

This is the other main mode of the program. The cutoff time, border dimensions and flow rate are specified as input. Thus, all design variables are input, which means that the required depth at the end of the field will usually not be achieved (ie, that under and/or over-irrigation can occur). The minimum infiltrated depth that occurs at the far end of the field is the main item that deter-

mines whether there is under or over-irrigation. It is therefore given as first output, together with the primary performance indicators: application efficiency, storage efficiency and distribution uniformity. This mode is most suitable for performance evaluation of an existing border irrigation system and for testing the performance sensitivity to a change in the field parameters.

## 6.2 Input windows

After you have selected a calculation mode, BORDEV will display the input screen for data entry: *Field Parameters* and *Input Decision Variables*. The input data to be provided in the two windows are summarised in Table 6.2.

### 6.2.1 Field parameters

#### *Infiltration*

Upon selection of the *Modified SCS families* type of infiltration data, BORDEV will use it for borders, as was discussed in Chapter 3, Section 1.1. One of seventeen families can be chosen. If a wrong number is typed, an error message with a list of acceptable numbers is shown. To select a particular family, you can use the Help screen by pressing [F1] while the cursor is on the family number. A screen with the possible numbers will pop up from which you can make your selection (Figure 6.1).

Table 6.2 Input variables for the Bordev calculation modes

Item	Fixed flow				Cutback flow				Tailwater reuse			
	Mode				Mode				Mode			
	1	2	3	4	1	2	3	4	1	2	3	4
<b>Field Parameters</b>												
Infiltration	0	0	0	0	0	0	0	0	0	0	0	0
Required depth	0	0	0	0	0	0	0	0	0	0	0	0
Flow resist.	0	0	0	0	0	0	0	0	0	0	0	0
Slope	0	0	0	0	0	0	0	0	0	0	0	0
<b>Input Decision Variables</b>												
Inlet flow rate		0	0	0		0	0	0		0	0	0
Length/width ratio		0				0				0		0
Border length	0		0	0	0		0	0	0		0	0
Border width	0		0	0	0		0	0	0		0	0
Cutoff time				0				0				
Advance ratio					0	0						
Cutback ratio					0	0	0	0				
Tailwater recovery ratio									0	0	0	0



FIELD PARAMETERS	INPUT DECISION VARIABLES
Intake family = <span style="background-color: black; color: white;">0.6</span> - Req. depth = 75 mm Flow resist. = 0.15 - Slope = 0.008 m/m	Flow rate = 25 l/s Border length = 150 m Border width = 20 m

Kostiakov-Lewis soil intake family	
Family #	Soil type
0.20	very heavy clay-loam
0.25	Heavy clay-loam
0.30	Moderately heavy clay-loam
0.35	Light clay-loam
0.40	Very light clay-loam
0.45	Very fine silty-loam
0.50	Fine silty-loam
<span style="background-color: black; color: white;">0.60</span>	<span style="background-color: black; color: white;">Moderately fine silty-loam</span>

scroll || | select intake family BORDEV

Figure 6.1 Intake family numbers to choose from

When you select a family number, the program uses the corresponding values  $A$ ,  $k$ , and  $f_0$  of the Kostiakov-Lewis equation (see Table 3.3). You can check this by selecting a family number, making a run, going back to the sub-module *Infiltration*, selecting the Kostiakov-Lewis equation mode, and returning to the input window again where you see the infiltration parameter values.

The values of the intake parameters  $A$ ,  $k$ , and  $f_0$  can be specified directly by selecting the *Kostiakov-Lewis equation*. Converting  $A$ ,  $k$ , and  $f_0$  values to other than the default units can be done as follows: go back to the *Units* menu, change time and depth units, and return to the input window again where the new values with their units will appear.

### *Required depth*

The depth to be infiltrated at the end of the border is the second input in the *Field Parameters* window. This target is determined outside BORDEV, as was explained in Chapter 3, Section 1.3.

### *Flow resistance*

The value of Manning's roughness coefficient ( $n$ ) can be specified in the *Field Parameters* window. Recommended values can be seen under the [F1] when the cursor is on the resistance value in the input screen.

### *Field slope*

The field slope of graded borders should neither be too high, to avoid erosion, nor too low, which would result in a too slow advance. Borders are usually best suited for slopes of less than 0.5 %. They could, however, also be used for slopes of more than 4 % where sod crops are grown. On most border slopes,

erosion is not a problem, except possibly at the head, where water velocity depends on the way in which the total inflow is supplied to the field (point-inlet, type of inlet structure, head ditch, siphons).

### **6.2.2 Decision variables**

Decision variables in surface irrigation are normally the field dimensions (length and width), flow rate, and cutoff time. Which of these parameters appear under the heading *Input Decision Variables* depends on the calculation mode you have selected (see Table 6.2).

#### *Border dimensions*

In Modes 1, 3 and 4 you can prescribe values for the border length and width. For open-ended borders, an optimum length applies. A field that is too long will result in a low performance because of a long advance time, with consequently an uneven infiltration and high deep percolation losses. On the other hand, a field that is too short would result in surface runoff that is too high. Consequently, for open-end borders, the optimum length (with all other variables given) is where the sum of deep percolation and surface runoff losses is at its minimum and hence the application efficiency is at its maximum.

#### *Length/width ratio*

In Mode 2, the length/width ratio is required to allow the program to calculate the border dimensions, based on a given flow rate.

#### *Flow rate*

In Modes 2, 3 and 4 you can assign values to the total flow rate available for the field. In BORDEV, this inflow rate is divided by the field width to obtain a unit flow rate per metre width, which is used in the numerical simulations. The flow rate should not be too low, otherwise the flow would not reach the end of the border. It should also not be too high, to avoid excessive runoff. Thus, with open-end borders, there is an optimum flow rate (similar to the optimum border length), whereby the sum of deep percolation losses and surface runoff losses is at its minimum, meaning a maximum application efficiency.

#### *Cutoff time*

In Modes 1, 2 and 3, the cutoff time is a result of the calculations. In Mode 4, a user-specified value can be given. For all three irrigation methods, cutoff is usually done some time after the end of advance, so that the required depth can infiltrate at the downstream end. When the cutoff time is substantially later than advance time, it will have a clear effect on recession, and thus on deep percolation and surface runoff losses. When cutoff is too early, the required depth at the end of the field may not be achieved.

### *Advance ratio*

The advance ratio, defined as the ratio of advance time to cutoff time, is especially of interest in cutback operation, where it can be either input or output, depending on the purpose (Mode) of the simulation.

### *Cutback ratio*

The cutback ratio must be specified in all calculation modes during a cutback operation. It is defined as the ratio of the reduced flow rate to the initial flow rate, such that the reduced flow is sufficient to keep the entire field length wetted as long as is necessary, while at the same time reducing the surface runoff. Because of the calculation algorithm used, cutback is assumed to be done when the water has reached the end of the field.

### *Tailwater reuse ratio*

The tailwater reuse ratio must be specified in all calculation modes for a reuse operation. It is defined as that part of the surface runoff that is reused and applied directly to calculate the application efficiency. A ratio of 1 would be ideal but may not always be possible, particularly because of high costs of the reuse system.

## **6.2.3 Input ranges**

Ranges have been fixed for all input variables as shown in Table 6.3 and are in metric units. If other units are chosen in the menu, the indicated ranges are converted in the program.

Table 6.3 Accepted ranges of input parameters

Input parameters	Accepted values
<b>Field Parameters</b>	
Intake family #	0.05 - 2.0
Infiltration coefficient, $k$	0.05 - 50 mm/min <sup>A</sup>
Infiltration exponent, $A$	0.01 - 0.8
Infiltration constant, $f_0$	0.005 - 30
Required depth, $D_{req}$	33 - 250 mm
Flow resistance, $n$	0.01 - 0.40
Field slope	0.0005 - 0.05 m/m
<b>Input Decision Variables</b>	
Border length, $L$	50 - 500 m
Border width, $W$	1 - 200 m
Length/width ratio, $L/W$	1 - 30
Flow rate, $Q$	1 - 250 l/s
Cutback ratio	0.65 - 1.00
Advance ratio	0.1 - 0.9
Tailwater reuse ratio	0.1 - 1.0
Cutoff time, $T_{co}$	10 - 2000 min

Based on a large number of runs, the ranges have been fixed in a bid to avoid too many impossible combinations and corresponding error messages. For all practical purposes, the ranges of the individual parameters will be more than sufficient. If you combine extreme values of the individual parameters you may not get a result. In that case, BORDEV will flash you a message on the screen indicating how to change these values in order to get a result.

The above ranges are ignored for output results, so, no warning will be given if such an out-of-range value is subsequently used as input in another mode.

## 6.3 Output Windows

When you have keyed in all the data, press [F2] for the calculations and the output. The screen again shows the two input windows, but a third window has now been added, showing the results (Figure 6.2). These results are presented in various groups, separated by a blank line. The first group contains the desired variable or variables according to the calculation mode you have selected: in Mode 1 they are the flow rate and the cutoff time; in Mode 2 the border length, the border width and the cutoff time; in Mode 3 the cutoff time; and in Mode 4 the minimum infiltrated depth.

The second group contains the primary performance indicators as discussed in Chapter 3, Section 3. All the calculation modes allow the performance of an irrigation scenario to be evaluated with the application efficiency, surface runoff ratio, deep percolation ratio, distribution uniformity and uniformity coefficient; Mode 4 adds the storage efficiency. Finally, using [PgDn], you

FIELD PARAMETERS	INPUT DECISION VARIABLES
Intake family = 0.6 -	Flow rate = 25 l/s
Req. depth = 75 mm	Border length = 150 m
Flow resist. = 0.15 -	Border width = 20 m
Slope = 0.008 m/m	

OUTPUT, Fixed flow, Mode 3	
Cut-off time	= 232 min
Applic. efficiency	= 65 %
Surf. run-off ratio	= 23 %
Deep perc. ratio	= 13 %
Distr. uniformity	= 84 %
unif. coefficient	= 94 %

F3 Graph F4 Save PgDn = Next window	BORDEV
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Figure 6.2 Bordev output example

obtain two groups with secondary output variables: times and depths. Outputs in all calculation modes are advance time, depletion time, recession time and intake opportunity time corresponding to the downstream point.

In all the calculation modes, BORDEV provides information on the maximum, minimum and average infiltrated amounts, together with the amount of surface runoff. In addition, Mode 4 also presents the amount of over/under-irrigation as the average amount over that part of the border that received deficit/excess irrigation. The output also includes the length of the border segment over which deficit and/or excess irrigation occurs.

The output results shown are dependent on the combination of *Operation* and *Calculation* modes. For the operation mode *Fixed flow* and *Tailwater reuse*, the output results of the various calculation modes are shown in Table 6.4 on the screen. For the operation mode *Cutback flow*, however, the cutback flow rate is added to the design variables for all calculation modes, while in Modes 3 and 4 the advance ratio is also added to this category.

Table 6.4 Output results for the Bordev calculation modes (Fixed flow system)

Output parameters	Mode 1	Mode 2	Mode 3	Mode 4
Design variables				
Border length		o		
Border width		o		
Flow rate	o			
Cutoff time	o	o	o	
Minimum infiltrated depth				o
Primary performance indicators				
Application efficiency	o	o	o	o
Surface runoff ratio	o	o	o	o
Deep percolation ratio	o	o	o	o
Storage efficiency				o
Distribution uniformity	o	o	o	o
Uniformity coefficient	o	o	o	o
Time variables				
Advance time	o	o	o	o
Depletion time	o	o	o	o
Recession time	o	o	o	o
Intake opportunity time	o	o	o	o
Infiltrated depths				
Maximum infiltrated depth	o	o	o	o
Minimum infiltrated depth	o	o	o	
Average infiltrated depth	o	o	o	o
Surface runoff	o	o	o	o
Over-irrigation				o
Under-irrigation				o
Length of over-irrigation				o
Length of under-irrigation				o

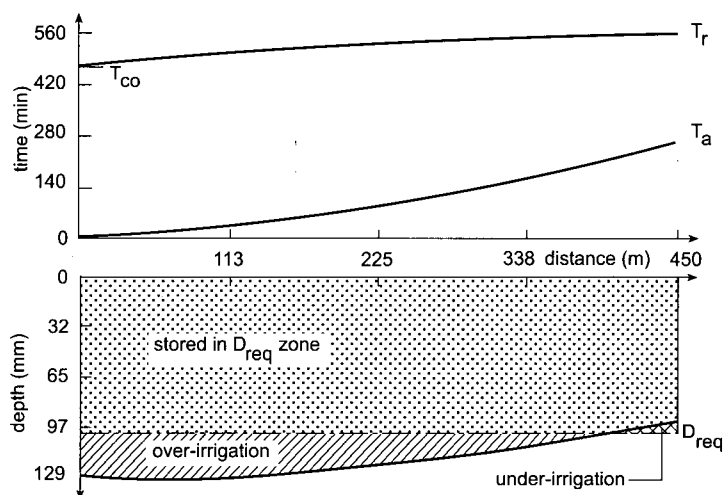


Figure 6.3 Graphical output of Bordev showing advance and recession curves and infiltration profile

By pressing the key [F3] you will see two graphs on your screen with the main results; the upper one shows advance and recession time in relation to border distance, while the lower one shows infiltrated depths along the border length. Note, that it is the recession curve that is depicted as with FURDEV, and not the cutoff time as with BASDEV. Under and over-irrigation are indicated, where applicable. This graph can be saved with [F8] or [F9]. Figure 6.3 shows the results of Run 3 of Example 1 (see Section 6.7.1 and Table 6.5).

The tabulated simulation results can be saved together with the input data, with [F4]. In a small window, the path (folder + file name) can be confirmed or changed, as described in Section 4.3.3. You can overwrite the previous file or append the current results to it. Further processing of the saved results file must be done under the *Files* menu, using *View/Print* (see Chapter 4, Section 4).

## 6.4 Error messages

BORDEV usually gives an output as a result of the calculations. Nevertheless, some variable and parameter combinations – mostly physically unrealistic combinations – could cause mathematical problems. When such problems are encountered, the program will terminate the calculation process and flash a message on the screen, typically containing two layers of information: the nature of the problem and suggestions on how to remedy it. Possible problems can be grouped into three categories: general advance time problems; advance time problems only related to the cutback system; and cutoff time problems.

### *General advance time problems*

This type of problem can occur with all three operation systems if the advancing front is unable to reach the downstream end of the border. Depending on the calculation mode, BORDEV will suggest increasing the flow rate and/or decreasing the length of the border to overcome the problem.

### *Advance time problem with cutback system*

In Calculation Modes 1 and 2, BORDEV calculates the required advance time as a function of the user-specified advance ratio and the required intake opportunity time. You can satisfy the advance time requirement by selecting an appropriate value of the flow rate in Mode 1 or that of the border length in Mode 2.

In Calculation Mode 1, the advance time associated with the maximum non-erosive flow rate can be longer than the required advance time. Here, the required advance time cannot be realised without using a flow rate that is greater than the maximum non-erosive one. This is clearly unacceptable. The only way out of this problem is to reduce the border length and/or increase the advance ratio. In addition, there are cases in which the flow rate that corresponds to the required advance time is shorter than the minimum flow rate required to advance to the downstream end of the border. When this happens, BORDEV will advise you to increase the border length and/or the advance ratio.

In Calculation Mode 2 – with some parameter and variable combinations – the required advance time could be greater than the advance time, corresponding to the maximum length to which the user-specified flow rate can advance. To overcome this difficulty, BORDEV will advise you to increase the flow rate and/or decrease the advance ratio.

### *Cutoff time problem*

In Calculation Modes 1, 2 and 3, the cutoff time is calculated so that the minimum infiltrated depth is equal to the required depth. In Mode 4, cutoff time is an input. If the user-specified cutoff time is too short, the calculated advance time could exceed it. This is a situation that cannot be handled by BORDEV. When such a problem is encountered, the screen message will recommend decreasing the border length and/or increasing the flow rate, and/or increasing the cutoff time.

## 6.5 Assumptions and limitations

The BORDEV program is based on the volume balance method, which is explained in detail in Appendix B. This method simulates the propagation of the wetting front along a unit width border strip during the advance phase. The ponding, depletion and recession phases are simulated using algebraic approaches. Some implicit assumptions used in the model are:

- The bed slope is greater than zero.
- The cutoff time is always greater than the advance time. This limitation is introduced to make sure that advance and recession do not occur simultaneously, a situation that the volume balance model cannot handle.
- The cross-sectional area of flow at the inlet of the border can be described by Manning's equation.
- The water depth is limited according to the unit width to ensure steady inflow.
- The infiltration can be described by the modified Kostiakov infiltration function.
- The upper boundary of the inflow is the maximum non-erosive flow rate, which can be calculated following the approach of Hart et al. (1980). The minimum flow rate is determined on advance considerations or the flow required for adequate spread, whichever is greater (Hart et al. 1980).

More detailed assumptions involved, particularly for the depletion and recession phases, are discussed in Appendix B. Apart from these theoretical assumptions related to the algorithms used, there are a number of more practical assumptions, which could be seen as limitations. The most important are:

- The flow rate is constant during the entire application period (unless cutback operation is applied).
- The conditions at the inlet enable the water to spread evenly over the entire width of the border strip.
- The bed slope is uniform along the border, and the cross slope is zero.
- The soil is homogeneous throughout the length of run of the border.
- The roughness coefficient is constant.

Finally it is assumed that the border is free draining at the end. The program cannot calculate the advance and recession curve for closed-end conditions, or for conditions where runoff water is collected to irrigate a flat extension at the end of the border. To reduce losses, and in particular runoff losses, the program offers the possibility of running the operation modes *Cutback flow* and *Tailwater reuse*. The program does not compute how the runoff water re-enters the system, which is controlled by local conditions. In the *Tailwater reuse* mode, a certain fraction of the runoff water specified by the user is assumed to be reused within the same border. In the *Cutback* mode, the assumption is that when water reaches the end of the border strip, the inflow is reduced to a value less than the inflow rate during the advance phase. The flow rate is constant before and after cutback.

The applicability of the BORDEV program is therefore bound by conditions that satisfy the assumptions stated above. Nevertheless, the simulation results with BORDEV will be in line with field observations, provided that the field conditions match the above-mentioned practical assumptions. As stated in the other programs, the BORDEV program only deals with the technical



and hydraulic aspects of border irrigation. The program should therefore be regarded as an aid in the design, operation and evaluation. Final decisions in the field will be controlled findings of the program in conjunction with agricultural, economic and social considerations.

## 6.6 Program usage

The following nine steps are important in the usage of the BORDEV program.

1. Start the SURDEV package. Select BORDEV from the main menu of SURDEV.
2. If you want to use an existing file, retrieve it with the *Load* command under the *Files* menu. If you want to make a completely new file, go straight to the *Calculation menu*, bypassing the *Files* menu and you will get a set of default data.
3. If you want to simulate cutback flow or reuse, go to the *Operation menu* and select the operation mode to work with. The program default operation mode is Fixed Inflow.
4. Select the *Units* menu only when you want to work with units other than the default units.
5. The default infiltration mode is the Modified SCS Families. If you prefer to work with another infiltration mode, go to the *Infiltration* menu.
6. Select a mode from the *Calculation* menu. Most work will be done in Modes 3 and/or 4. Less experienced users can start in Mode 1 or 2 to get a first estimate of the flow rate or field dimensions, respectively. Mode 4 can be used to evaluate existing situations or to do sensitivity analyses.
7. In the input window, Field parameters and Decision variables can be specified, after which the program can be run with [F2].
8. You can view the results of each run in tabular form in the output window, or in graphical form using [F3]. The results of one simulation run (output and input in one file) can be saved in a separate file or can be appended to earlier runs in an existing file with [F4].
9. Select *Files* and *View/Print* from the main menu to see what has been done and/or to print a file directly, or convert it to a print file for a word-processor program, or convert it to a file to be imported in a spreadsheet program where you can make your own graphs.

## 6.7 Sample problems

In most cases, the user will not be satisfied with a solution obtained after one run, and will usually do a number of runs to get an acceptable solution. Two simple examples are given to illustrate this procedure. For more elaborate problems, see Chapter 8, Section 2.

### 6.7.1 Fixed flow system

An operation practice is to be developed for a fixed-flow border irrigation system. The field in which the system is to be installed is 450 m long in the direction of the main slope. The individual borders are 20 m wide. The soil is silty loam and can be classified by the intake family # 0.5. The net irrigation requirement is 100 mm. Other input values are default. The flow rate is to be determined in such a way that the application efficiency is at least 70 per cent and the cutoff time has a practical value.

1. We want to make a new file, and therefore do not need to use the *Files* sub-menu. Note, the operation, units and parameter modes and values to be used in this example are the default ones, so we can go directly to the *Calculation* menu and select *Mode 1: Flow Rate*. Enter the above values in the two input windows and make a run.
2. The results of this run (Table 6.5, Run 1) show that at a rate of 47 l/s, a border of 450 m long and 20 m wide can be irrigated with an application efficiency of 66 per cent. The corresponding uniformity coefficient is 91 per cent and the distribution uniformity is 78 per cent. This application efficiency is too low. Increase the flow rate to 50 l/s and run BORDEV in Mode 3 and observe the effect.
3. This run (Table 6.5, Run 2) reveals the application efficiency to be the same as before, which is still below the target efficiency. The cutoff time decreased from 485 to 457 minutes, but is still an impractical value. Next we make a run in Mode 4 to see the effect when the cutoff time is reduced from 457 to 420 minutes (7 hours);
4. With this run (Table 6.5, Run 3) the reduced cutoff time results in an application efficiency of 71 per cent, which is acceptable. The corresponding uniformity coefficient is 91 per cent and the distribution uniformity is 78 per cent. But, the consequence of reducing the cutoff time is also a slight under-irrigation: the minimum infiltrated depth is now 92 mm instead of 100 mm. Over the lower 56 m of the border, the average depth infiltrated would be 4 mm less than that required. The upper 394 m of the border would receive an over-irrigation of 20 mm. These results are acceptable.

Table 6.5 can be made with BORDEV. The procedure is as follows. Save Run 1 with [F4] and prescribe a particular file name (EXAMPLE1). BORDEV automatically adds the extension .BDR to this file name. Save Runs 2 and 3 with [F4] under the same file name using the *Append* option. Go back to the main menu, go to *Files* menu, select *Print/View*, then EXAMPLE1. See the results and select [F5] (*Print/Save*) and then the option *Text file*. BORDEV now automatically adds the extension .TXT to the file name EXAMPLE1. If you now go out of BORDEV, you can load the results in a word-processing program by retrieving the file EXAMPLE1.TXT. This is how you make Table 6.5.

Table 6.5 Bordev program for sloping border irrigation (Filename: EXAMPLE1)

Run no.		1	2	3
Type of system		1	1	1
Calculation Mode		1	3	4
<hr/>				
Input Parameters	Units			
Flow rate	l/s	—	50	50
Length	m	450	450	450
Width	m	20	20	20
Cutoff time	min	—	—	420
Required depth	mm	100	100	100
Flow resistance	—	0.15	0.15	0.15
Bed slope	m/m	0.008	0.008	0.008
Intake family	—	0.5	0.5	0.5
<hr/>				
Output Parameters				
Flow rate	l/s	47.02	—	—
Cutoff time	min	485	457	—
Application eff.	%	66	66	71
Storage eff.	%	100	100	99
Uniform. coeff.	%	91	92	91
Distrib. unif.	%	78	80	78
Deep perc. ratio	%	19	16	13
Runoff ratio	%	15	18	16
Avg. inf. depth	mm	128	125	117
Max. inf. Depth	mm	142	137	129
Min. inf. depth	mm	100	100	92
Surface runoff	mm	23	28	23
Over-irrigation	mm	28	25	20
Under-irrigation	mm	0	0	4
Over-irr. Length	m	450	450	394
Under-irr. Length	m	0	0	56
Advance time	min	287	260	260
Depletion time	min	542	514	476
Recession time	min	627	599	560
Opportunity time	min	339	339	300

The above problem concerned the *Fixed flow* operation mode. For the same situation as described above, BORDEV will now be used in the design of a *Cutback flow* operation mode.

### 6.7.2 Cutback flow system

This sample problem is presented to illustrate how the irrigation performance under the fixed flow system of Section 6.7.1 can be improved by switching to the cutback flow system.

1. Go to the *Operations* menu and select *Cutback flow*. Go to the *Calculation* menu and select Mode 1: *Flow rate*. Enter the same values in the two input windows as in Table 6.5 and make a run. Keep the default Advance Ratio at 0.33 and the default Cutback Ratio at 0.65.
2. The results of this run (Table 6.6, Run 1) show that at a flow rate of 69 l/s, a border 450 m long and 20 m wide can be irrigated with an application efficiency of 73 per cent. Once the water has reached the end of the border, the flow rate is reduced to 45 l/s. A cutoff time of 366 minutes is required.

Table 6.6 Bordev program for sloping border irrigation (Filename: EXAMPLE2)

Run no.		1	2	3
Type of system		2	2	2
Calculation Mode		1	3	4
<hr/>				
Input Parameters	Units			
Flow rate	l/s	–	70	70
Length	m	450	450	450
Width	m	20	20	20
Cutoff time	min	–	–	300
Advance ratio	–	0.33	–	–
Cutback ratio	–	0.65	0.65	0.65
Required depth	mm	100	100	100
Flow resistance	–	0.15	0.15	0.15
Bed slope	m/m	0.008	0.008	0.008
Intake family	–	0.5	0.5	0.5
<hr/>				
Output Parameters				
Flow rate	l/s	69.1	–	–
Cutback flow	l/s	44.92	45.5	45.5
Cutoff time	min	366	364	–
Cutback time	min	167	164	164
Advance ratio	–	–	0.45	0.55
Application eff.	%	73	73	82
Storage eff.	%	100	100	97
Uniformity coeff.	%	95	95	94
Distrib. unif.	%	88	89	86
Deep perc. ratio	%	13	13	4
Runoff ratio	%	14	14	13
Avg. inf. Depth	mm	113	113	99
Max. inf. depth	mm	119	119	106
Min. inf. depth	mm	100	100	86
Surface runoff	mm	23	24	18
Over-irrigation	mm	13	13	4
Under-irrigation	mm	0	0	6
Over-irr. Length	m	450	450	244
Under-irr. Length	m	0	0	206
Advance time	min	167	164	164
Depletion time	min	425	422	358
Recession time	min	506	504	437
Opportunity time	min	339	339	272

The corresponding uniformity coefficient is 95 per cent and the distribution uniformity 88 per cent. We run BORDEV in Mode 3 to see the effect when the flow rate is increased to a practical value of 70 l/s.

3. The outcome of this run (Table 6.6, Run 2) show that the application efficiency and the cutoff time remain practically the same (because of the slight difference in flow rate). The cutoff time, however, has an impractical value. Now go to Mode 4 to see the effect when this is reduced from 364 to 300 minutes.
4. This run (Table 6.6, Run 3) shows that this reduction in cutoff time results in an application efficiency of 82 per cent. The corresponding uniformity coefficient is 94 per cent and the distribution uniformity is 86 per cent. Obviously, the reduced cutoff time also results in some under-irrigation: the minimum infiltrated depth is now 86 mm instead of 100 mm. Over the lower 206 m of the border, the average depth infiltrated would be 6 mm less than that required. The upper 244 m of the border would receive an over-irrigation of 4 mm. These results are acceptable.

A comparison of Tables 6.5 and 6.6 shows that a cutback flow operation mode can increase the application efficiency from 71 to 82 per cent, which is a considerable improvement.

Table 6.6 was also made with BORDEV. Once you are familiar with the foregoing basic elements of working with BORDEV, you can do more elaborate work, examples of which are presented in Chapter 8. These concern several sets of runs with which various relationships can be established. This not only illustrates the potential of the program, but also provides a deeper insight into the complex nature of the border irrigation process.



## 7 FURDEV user manual

FURDEV is a modular, menu-driven computer program developed to solve problems in the design, operation and evaluation of furrow irrigation systems. FURDEV deals with the flow in one furrow and does not provide suggestions for field layout design. You start the program by selecting it in the SURDEV package. The installation procedure of this package was discussed in Chapter 4, Section 1.

### 7.1 Menu structure

There are six main menu items, five of which have sub-menus that you can select by moving the highlight with the arrow keys and pressing [ENTER], or by typing the red (bold) character. Table 7.1 shows the structure of the main menu and its first layer of sub-menus.

#### 7.1.1 Sub-menu files

The sub-menu *Files* has two options: *Load* and *View/Print*. With *Load*, you can select an existing file and continue with the calculations. With *View/Print*, you can select an existing file, the contents of which will subsequently be displayed on the screen. Pressing [F5] gives you the option to print this file or to save it as a text file, or a spreadsheet file. For more information on these topics, see Chapter 4, Section 4.3.

#### 7.1.2 Sub-menu operation

You can select the appropriate system operation mode from the sub-menu *Operation*. Selecting *Fixed flow* means that a constant inlet flow rate is used to irrigate the furrows during the entire application time. *Cutback flow* means that at the end of advance the initial inflow is reduced once for the remainder

Table 7.1 Furdev menu structure

Files	Operation	Units	Parameters	Calculation	Quit
Load	Fixed flow	Flow rate	Infiltration	1. Flow rate	
View/Print	Cutback flow	Length	Geometry	2. Length	
	Tailwater reuse	Amount/depth		3. Cutoff time	
		Time		4. Min. Amount	

of the application time. *Tailwater reuse* represents a furrow irrigation system with a runoff reuse arrangement. Because FURDEV only simulates the flow in one furrow, the reuse component is not integrated in the required flow rate of another furrow. The default operation mode is *Fixed flow*.

### 7.1.3 Sub-menu units

In the sub-menu *Units*, you can choose pre-determined units for flow rate, length, amount, and time. The following units are available:

- Flow rate: litres per second, US gallons per minute, cubic metres per minute, or cubic feet per minute.
- Length: metres or feet, used for furrow length.
- Amount/depth: millimetres, inches, cubic metres per metre length of furrow, or cubic feet per foot length of furrow. These are used for the various supplied and infiltrated amounts or depths.
- Time: minutes or hours, used not only for advance, cutoff, depletion, and recession times, but also in the infiltration parameters.

Because FURDEV simulates the flow in one furrow, the spacing of the furrows is a parameter for the actual amount of infiltrated irrigation water. When you select millimetres or inches, the quantity of infiltrated irrigation water is expressed as the depth of water, and the program transforms this value internally to a volume per metre length of furrow by taking into account the selected furrow spacing. When you select cubic metres (or feet) per metre (or foot) length of furrow, then the actual depth of infiltrated irrigation water will depend on the chosen spacing of the furrows.

The selected units are maintained throughout the program and are also saved with the file. When the program is started default units are: litres per second for flow rate; metres for furrow length; millimetres for infiltrated depths; and minutes for time.

### 7.1.4 Sub-menu parameters

The sub-menu *Parameters* allows you to select the mode in which you want to characterise the infiltration characteristics of the soil (*Infiltration*) as well as the geometry of the furrow cross-section (*Geometry*).

#### *Infiltration*

Within the program, all infiltration calculations are based on the infiltration characteristics of a soil as described by the Kostiaikov-Lewis equation (Equation 3.4)



$$D_i = kT^A + f_0T$$

where  $D_i$  is the cumulative infiltration depth after an infiltration opportunity time  $T$ ,  $k$  is the infiltration constant,  $A$  is the infiltration exponent, and  $f_0$  is the basic infiltration rate. The menu offers three options for entering the soil infiltration characteristics. These are:

- Indirectly by using *Intake family*;
- Directly by specifying values for  $A$ ,  $k$  and  $f_0$  in the Kostiakov-Lewis equation;
- Determining a kind of average furrow infiltration parameter from *Field data* on advance times.

For more background information on this subject, see Chapter 3, Section 1.1. The default infiltration input mode is *Intake family*.

### Geometry

All surface flow calculations in the program are based on the furrow geometry expressed in terms of the furrow geometry parameters  $\sigma_1$ ,  $\sigma_2$ ,  $\tau_1$ , and  $\tau_2$ . For more information on these parameters, see Section 7.2.1 and Appendix B.

In the sub-sub-menu *Geometry*, these parameters can be specified under the *Sigma & tau* option. Because of the complexity of these parameters, however, FURDEV also offers you the option *Cross-section type* where you can simply indicate one of three cross-sectional shapes that is the closest match to the real cross-section of the furrow. Here, you can choose between *Triangular*, *Parabolic*, or *Trapezoidal* (Figure 7.1). Later on, in the input windows, you will be required to specify the characteristic data for the selected cross-section

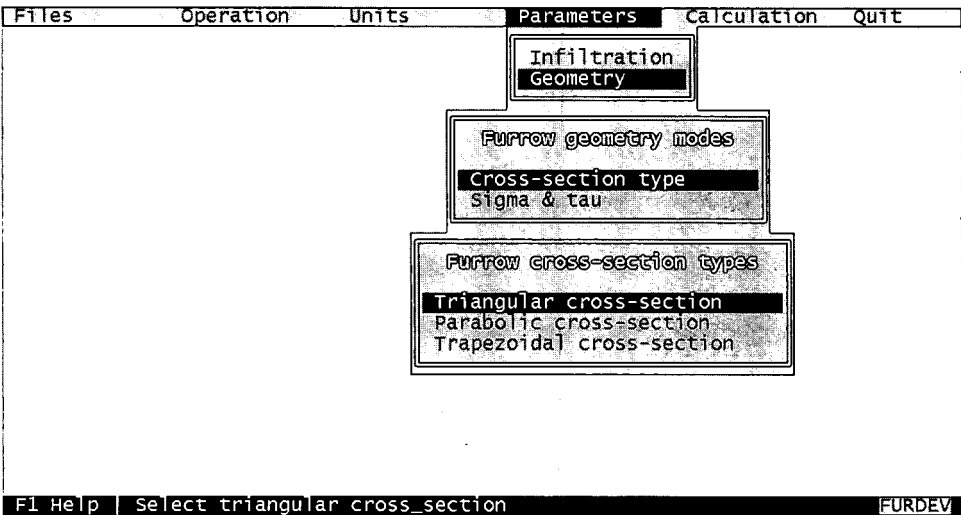


Figure 7.1 Selecting a furrow cross-section in Furdev

(eg, flow depth, side slope, top width, etc). Using these data, the program will calculate the corresponding furrow geometry parameters  $\sigma_1$ ,  $\sigma_2$ ,  $\tau_1$ , and  $\tau_2$ .

The default geometry input mode is *Cross-section type* and the default furrow cross-section shape is *Triangular*.

### 7.1.5 Sub-menu calculation

The sub-menu *Calculation* is the only place in FURDEV where input data can be entered. Before entering data, however, you have to select one of four different calculation modes (Table 7.1). What the first three modes have in common is that the calculated minimum infiltrated depth at the downstream end of the furrow always equals the required depth. In other words, no under-irrigation will occur in the downstream end, whereas over-irrigation will always occur in the upstream part. When to use the various modes is summarised below:

#### *Calculation Mode 1: Flow Rate*

Calculation Mode 1 is primarily for design purposes, when you know the length of the furrow and want to know the approximate flow rate that is needed to achieve a reasonable performance. The program will also give you the required cutoff time and the primary performance indicators as well as various depth and time parameters.

For *Fixed flow* and *Tailwater reuse* operation modes, FURDEV calculates the flow rate in such a way that the application efficiency is maximised. For the *Cutback flow* operation mode, FURDEV calculates the flow rate so that the user-specified advance ratio is achieved. Although the result obtained in Mode 1 is close to these targets, it is advisable to continue running in Modes 3 and or 4, because in most cases refinements will still be necessary.

#### *Calculation Mode 2: Furrow Length*

Calculation Mode 2 is the reverse of Calculation Mode 1: the flow rate is now known and you want to know the approximate furrow length that is needed to achieve a reasonable performance. The program will also give you the required cutoff time and the primary performance indicators as well as various depth and time parameters. Here too it is necessary to continue in Modes 3 and/or 4 to get the final result.

#### *Calculation Mode 3: Cutoff Time*

Here, both the flow rate and furrow length are input. The required cutoff time is the resulting design variable, while also the application efficiency and secondary output parameters are given. Note, in this mode the advance ratio is an output. This is because it is impossible to fix advance ratio, length, and flow rate and at the same time satisfy the requirement that the minimum infiltrated depth equals the required depth.

### Calculation Mode 4: Minimum Depth

Here, the cutoff time is also specified as input, in addition to the furrow length and the flow rate. Thus, all design variables are now input, which means that the required depth at the end of the field will usually not be achieved (ie, that under and/or over-irrigation can occur). The minimum infiltrated depth that occurs at the far end of the field is the determining factor of whether there is under or over-irrigation. It is therefore given as first output, followed by the primary performance indicators: application efficiency, storage efficiency and distribution uniformity. This mode is most suitable for a performance evaluation of an existing furrow irrigation system and for testing the performance sensitivity to a change in the field parameters.

## 7.2 Input windows

When you have selected a calculation mode, FURDEV will display the input screen for data entry. The input data to be provided in these windows are summarised in Table 7.2.

The box located in the upper left corner of the screen (Figure 7.2) contains all the field parameters, except infiltration. Directly below is the box containing infiltration data. The contents of these two boxes, particularly those items pertaining to *Geometry* and *Infiltration*, vary depending on the option selected under the sub-menu *Parameters*. With normal usage of the program, the

Table 7.2 Input variables for the Furdev calculation modes

Item	Fixed flow				Cutback flow				Tailwater reuse			
	Mode				Mode				Mode			
	1	2	3	4	1	2	3	4	1	2	3	4
<b>Field Parameters</b>												
Required depth	0	0	0	0	0	0	0	0	0	0	0	0
Max. velocity	0	0	0	0	0	0	0	0	0	0	0	0
Flow resistance	0	0	0	0	0	0	0	0	0	0	0	0
Slope	0	0	0	0	0	0	0	0	0	0	0	0
Spacing	0	0	0	0	0	0	0	0	0	0	0	0
Geometry	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration	0	0	0	0	0	0	0	0	0	0	0	0
<b>Input Decision Variables</b>												
Inlet flow rate		0	0	0		0	0	0		0	0	0
Furrow length	0		0	0	0		0	0	0		0	0
Cutoff time				0				0				0
Advance ratio					0	0						
Cutback ratio					0	0	0	0				
Tailwater recovery ratio									0	0	0	0

FIELD PARAMETERS	INPUT DECISION VARIABLES		
Required depth = 75 mm Max. velocity = 13.8 m/min Flow resist. = 0.04 - Slope = 0.005 m/m Spacing = 1 m Side slope = 2 m/m	Flow rate = 0.5 l/s Length = 200 m		
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: center; padding: 5px;">FIELD PARAMETERS (INFILTRATION)</th> </tr> </thead> <tbody> <tr> <td style="padding: 5px;">Intake family = 0.6 -</td> </tr> </tbody> </table>		FIELD PARAMETERS (INFILTRATION)	Intake family = 0.6 -
FIELD PARAMETERS (INFILTRATION)			
Intake family = 0.6 -			
<div style="display: flex; justify-content: space-between; border-top: 1px solid black;"> <span>F2 Calculate   Edit input parameters for calculation mode 3</span> <span>FURDEV</span> </div>			

Figure 7.2 Entering system parameters in Furdev

values of the field parameters will be given once for a particular situation and will be changed only to make sensitivity analyses after satisfying results have been obtained in Mode 3 or 4. Detailed examples can be found in Chapter 8, Section 3.2.

The decision variables are displayed in the box located at the upper right corner of the input screen. The data to be entered here depends on the selected *Calculation* mode and the selected *Operation* mode.

## 7.2.1 Field parameters

### *Required depth*

The required depth to be infiltrated at the end of the furrow is the first input in the *Field Parameters* window. This target depth is determined outside FURDEV, as was indicated in Chapter 3, Section 1.3.

### *Non-erosive velocity*

The flow velocity in the furrow should not exceed a maximum, non-erodible value, which depends on the soil type. It is usually taken at about 8 m/min in erosive silty soils and up to about 13 m/min in more stable clay and sand soils (see Section 3.1.4). This maximum occurs in the first part of the furrow.

### *Flow resistance*

Fangmeier and Ramsey (1978), when investigating furrow infiltration, found values ranging between 0.02 and 0.04. SCS (USDA 1983) states that a flow resistance of 0.04 is appropriate for furrows. No further details are given. In

contrast to basin and border irrigation, there are no crops in the furrow, consequently, the range of  $n$ -values is smaller. Walker (1989) uses this  $n = 0.04$  in all calculation examples. See also Section 3.1.2.

#### *Field slope*

The field slope of graded furrows should neither be too high, to avoid erosion, nor too low, which would result in a slow advance. For furrows, suitable slopes normally vary between 0.05 and 1 per cent. Small furrows and corrugations, however, can be used on steeper slopes up to 2 per cent.

#### *Furrow spacing*

The furrow spacing is a dual-purpose parameter. In the first place, it is a field dimension, which is primarily used to convert volumes to depths. But, it is also used for modelling the infiltration process, where the furrow spacing is used to convert the  $A$ ,  $k$  and  $f_0$  values corresponding to the modified SCS intake families.

The input value should not conflict with the given furrow geometry. Just suppose that you have specified a trapezoidal section with 1.5:1 side slope and 0.1 m bed width. Suppose also that in your field the depth of the furrows is 20 cm and the top width of the ridges is 25 cm. The actual spacing should then be equal to  $12.5+30+10+30+12.5=95$  cm.

#### *Furrow geometry*

Under this menu there are two sub-options: *Cross-sectional type* and *Sigma & tau*. The second option refers to the parameters  $\sigma_1$ ,  $\sigma_2$ ,  $\tau_1$  and  $\tau_2$  that are used in the program to specify the furrow cross-section. For details, see Appendix B. Because most users would not know which value to give here, and calculating the parameters could be a tiresome job, the program offers the easier option of just specifying the furrow shape by selecting *Cross-sectional type*.

If you select *Triangular* as the cross-sectional shape, the input window will ask you to specify only the side slope of the furrow cross-section. If you select *Parabolic*, you need to specify the maximum depth and the corresponding water top width, either estimated or obtained from field measurements. If you select *Trapezoidal*, you need to enter the side slope and the bed width.

For all three cross-sectional shapes, the program will transform the given input values into the corresponding geometry parameters  $\sigma_1$ ,  $\sigma_2$ ,  $\tau_1$  and  $\tau_2$ . You can check this by selecting a particular cross-sectional shape, entering the required input data, making a run, going back to the sub-menu *Parameters*, selecting *Geometry* and *Sigma & tau* mode, and returning to the input window again.

When selecting the geometry shape and geometry parameters, care should be taken that the geometry and spacing are not conflicting. For instance, the combination of small spacing with a wide and deep trapezoidal section may be geometrically impossible. In such cases, if impossible combinations are

entered as input, FURDEV will flash you a message to that effect on your screen, see Section 7.4.

### *Infiltration*

When the *Intake family* type of infiltration data is selected, FURDEV uses the modified SCS families for furrows, as was discussed in Chapter 3, Section 1.1. Seventeen families can be chosen. If a wrong number is typed, you will get an error message on your screen with a list of acceptable numbers. To select a particular family, you can get Help by pressing [F1] while the cursor is on the family number. A help screen will pop up from which you can make your selection, using the upward and downward arrow keys.

Upon selection of a family number, the corresponding values  $A$ ,  $k$ , and  $f_0$  of the Kostiakov-Lewis equation (as shown in Table 3.3) will give you the "soil infiltration parameters", as determined from infiltrometer measurements, for instance. To simulate the furrow infiltration, these are converted to "furrow infiltration parameters". In furrows, infiltration takes place along the wetted perimeter of the furrow and is assumed to spread in the soil over the width of the furrow spacing (see Jensen 1980, and Walker 1989). The values of Table 3.3 are therefore adjusted by using the ratio of wetted perimeter to furrow spacing. Once you make a run with FURDEV, this is automatically done within the program. You can check this by selecting a family number, making a run, going back to the sub-module *Infiltration*, selecting the *Kostiakov-Lewis equation* mode, and returning to the input window again, where you then see the adjusted "furrow infiltration parameters".

When you select the *Kostiakov-Lewis equation*, you can specify the values of the intake parameters  $A$ ,  $k$ , and  $f_0$  directly. Note, these values represent the "furrow values" and therefore include the two-dimensional infiltration process. In other words, these parameter here should have been obtained from furrow infiltration trials and do not represent the infiltration characteristics of the soil for a flat surface.

Converting the intake parameters to values other than default units can be done as follows: Go back to the *Units* menu, change time and amount/depth units, and return to the *Field Parameters* input window, where the new values and their units will appear.

When the *Field data* option is selected, enter the data obtained from field infiltration tests as input, based on which FURDEV will calculate the corresponding infiltration parameters. Logically, these are the "furrow infiltration parameters", already including the two-dimensional aspect. To estimate the infiltration parameters of the modified Kostiakov equation, the "two-point method" (Elliott and Walker 1982) is applied in the program. The data you now need to prescribe are: flow rate, stable tailwater runoff (the runoff rate after the runoff hydrograph levels off), advance time to downstream end of furrow, advance time to halfway down the furrow, furrow length and furrow bed slope. Note, only the spacing belonging to the field measurements must be

entered under *parameters Field*. For more information on this option, see Appendix B.

The above difference between “soil” parameters and “furrow” parameters implies that one has to be careful when changing from one infiltration mode to another, because the infiltration parameters for the *Intake family* option are not the same as those used for the other two options.

### 7.2.2 Decision variables

The decision variables in surface irrigation are normally the field dimensions (furrow length and spacing), the flow rate, and the cutoff time. It depends on the calculation mode that you have selected which of these parameters appear under the heading “Decision variables” (see Table 7.2).

#### *Furrow length*

For open-ended furrows, there is an optimum length, giving a maximum possible application efficiency. Too long a field will result in poor performance because of a long advance time, with uneven infiltration and excessive deep percolation losses in the upstream part of the field. On the other hand, too short a field would result in excessive surface runoff. Consequently, there is one length (with all other variables given) for open-end furrows, for which the sum of deep percolation and surface runoff losses is at its minimum and the application efficiency is at its maximum.

#### *Flow rate*

For furrows, the flow rate is the inflow into one furrow, representing the unit flow rate per width of one furrow spacing. It should not be too low, otherwise the flow would not reach the end of the furrow, and it should not be too high to avoid scouring. In the case of open-end furrows there is also an optimum flow rate (similar to the furrow length), where the sum of deep percolation losses and surface runoff losses is at its minimum.

#### *Cutoff time*

For all three irrigation methods, cutoff is usually done some time after the end of advance to achieve infiltration of the required depth at the downstream end. If the cutoff time is much later than the advance time, it will have a clear effect on the deep percolation and surface runoff losses. If cutoff is too early, this will often result in not achieving the required depth at the end of the field.

#### *Cutback ratio*

The cutback ratio, defined as the ratio of reduced flow rate to the initial flow rate, must be such that the reduced flow is sufficient to keep the entire field

length wetted for as long as is necessary, while at the same time reducing the surface runoff. In the simulation process, cutback is assumed to be done when the water has reached the end of the field.

### *Advance ratio*

The advance ratio, defined as the ratio of advance time to cutoff time, is of special interest with cutback systems where it can be simulation input or output, depending on the purpose of the simulation. Too low a ratio means too short a cutoff time, and a high ratio a long cutoff time, both with the consequences mentioned under *Cutoff Time*. A small advance ratio means a fast advance and hence a higher flow rate, which is generally recommendable.

### *Tailwater reuse ratio*

The tailwater reuse ratio, giving that part of the surface runoff that is reused, allows us to calculate the application efficiency directly. A ratio of 1 would be ideal but may not always be possible, particularly because of the high costs involved.

## **7.2.3 Input ranges**

Ranges have been fixed for all input variables, as shown in Table 7.3 and are in metric units. If other units are chosen in the menu, the indicated ranges are converted in the program.

Table 7.3 Accepted ranges of input parameters

Input parameters	Accepted values
<b>Field Parameters</b>	
Required depth, $D_{\text{req}}$	25 - 250 mm
Maximum velocity	7 - 15 m/min
Flow resistance, $n$	0.01 - 0.08
Furrow slope, $S_0$	0.0003 - 0.03 m/m
Furrow spacing, $W_s$	0.5 - 1.5 m
Side slope, $z$	0.5 - 3.0 m/m
Intake family #	0.05 - 2.0
Infiltration coefficient $k$	0.050 - 30 mm/min <sup>A</sup>
Infiltration exponent $A$	0.01 - 0.7
Infiltration constant $f_0$	0.005 - 10 mm/min
<b>Input Decision Variables</b>	
Furrow length, $L$	5 - 700 m
Flow rate, $Q$	0.02 - 16.67 l/s
Cutback ratio	0.65 - 1.00
Advance ratio	0.1 - 0.9
Tailwater reuse ratio	0.1 - 1.0
Cutoff time, $T_{\text{co}}$	10 - 2000 min



Based on a large number of runs, the ranges have been fixed in a bid to avoid too many impossible combinations and corresponding error messages. For all practical purposes, the ranges of the individual parameters will be more than sufficient. If you combine extreme values of the individual parameters, you may not get a result. FURDEV will then flash you a message on the screen indicating how to change these values in order to get a result.

For output results, the above ranges are ignored. So, if such an out-of-range value is subsequently used as input in another mode, no warning will be given.

### 7.3 Output windows

After all the input has been entered, press [F2] for the calculations and the output. The screen again shows the three input windows, but a fourth window has now been added showing the results (Figure 7.3). These results are presented in various groups, separated by a blank line. The first group contains the desired decision variable or variables, according to the calculation mode you have selected: in Mode 1 they are the flow rate and the cutoff time; in Mode 2 the furrow length and cutoff time; in Mode 3 the cutoff time; and in Mode 4 the minimum infiltrated depth.

The second group contains the primary performance indicators as discussed in Chapter 3, Section 3. All the calculation modes allow the performance of an irrigation scenario to be evaluated with the application efficiency, the surface runoff ratio, the deep percolation ratio, the distribution uniformity, and the uniformity coefficient; Mode 4 adds the storage efficiency. Note, the first three indicators also represent the overall water balance of the furrow.

FIELD PARAMETERS		INPUT DECISION VARIABLES	
Required depth	= 75 mm	Flow rate	= 0.5 l/s
Max. velocity	= 13.8 m/min	Length	= 200 m
Flow resist.	= 0.04		
Slope	= 0.005 m/m		
Spacing	= 1 m		
Side slope	= 2 m/m		
FIELD PARAMETERS (INFILTRATION)		OUTPUT, Fixed flow, Mode 3	
Intake family	= 0.6	Cut-off time	= 707 min
		Applic. efficiency	= 71 %
		Surf. run-off ratio	= 12 %
		Deep perc. ratio	= 17 %
		Distr. uniformity	= 80 %
		Unif. coefficient	= 93 %

F3 Graph F4 Save PgDn = Next window

FURDEV

Figure 7.3 Results screen in Furdev

Finally, there are two groups of secondary output variables in all the calculation modes. These concern times and depths and are: advance time, depletion time, recession time, and intake opportunity time corresponding to the downstream point. Note, all the "time" values are counted from zero (ie, from the start of the irrigation). The duration of a phase is the difference between two times, for instance, the duration of the depletion period equals the depletion time minus cutoff time.

In all calculation modes, FURDEV provides information on the maximum, minimum, and average infiltrated amounts, together with the surface runoff. In addition, Mode 4 also presents the amount of over and under-irrigation as the average amount over that part of the furrow where this has occurred, and includes the length of the furrow segment on which it occurs.

The output results shown are dependent on the combination of *Operation* and *Calculation* modes. Table 7.4 shows the output results for the operation mode *Fixed flow*. The program also presents the same output results for the

Table 7.4 Output results for the Furdev calculation modes (Fixed flow system)

Output parameters	Mode 1	Mode 2	Mode 3	Mode 4
Design variables				
Furrow length		0		
Flow rate	0			
Cutoff time	0	0	0	
Minimum infiltrated depth				0
Primary performance indicators				
Application efficiency	0	0	0	0
Surface runoff ratio	0	0	0	0
Deep percolation ratio	0	0	0	0
Storage efficiency				0
Distribution uniformity	0	0	0	0
Uniformity coefficient	0	0	0	0
Time variables				
Advance time	0	0	0	0
Depletion time	0	0	0	0
Recession time	0	0	0	0
Intake opportunity time	0	0	0	0
Infiltrated depths				
Maximum infiltrated depth	0	0	0	0
Minimum infiltrated depth	0	0	0	
Average infiltrated depth	0	0	0	0
Surface runoff	0	0	0	0
Over-irrigation				0
Under-irrigation				0
Length of over-irrigation				0
Length of under-irrigation				0

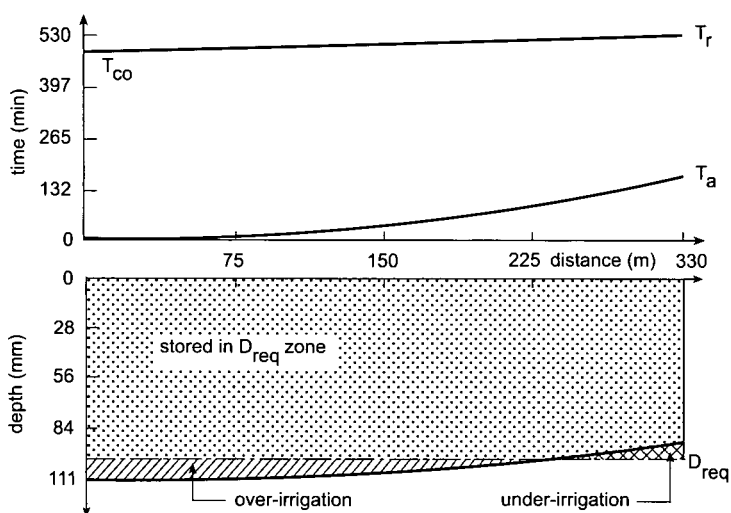


Figure 7.4 Advance curves, recession curves, and infiltration profiles in Furdev

operation mode *Tailwater reuse*. For the operation mode *Cutback flow*, however, and for all calculation modes, the cutback flow rate is added to the output variables; in Modes 3 and 4, the advance ratio is added as well.

By pressing [F3], you will see two graphs showing the main results: the upper one shows advance and recession times in relation to furrow distance, while the lower one shows the infiltrated depths along the furrow length. Under and over-irrigation are indicated where applicable. This graph can be saved with [F8] or [F9]. Figure 7.4 shows a graph of the results of Run 3 from Example 1 (see Table 7.5). Note, here the recession time is depicted and not the cutoff time as with BASDEV.

The tabulated simulation results can be saved, together with the input data with [F4]. In a small window, the path (directory + file name) can be confirmed or changed, as described in Section 4.3.3. You can overwrite the previous file or append the current results to it. Further processing of the saved results file must be done under the *Files* menu using *View/Print*. See Section 4.4.

## 7.4 Error messages

FURDEV usually gives an output as a result of the calculations. Nevertheless, some combinations of variables and parameters – mostly physically unrealistic combinations – could cause mathematical problems. When such problems are encountered, the program terminates the calculation process and flashes a message on the screen. The message typically contains two layers of information: the nature of the problem and suggestions on how to remedy it.

Possible problems can be grouped into three categories: general advance time problems, advance time problems related only to the cutback system, and cut-off time problems.

#### *General advance time problem*

The problem with the advancing front being unable to reach the downstream end of the furrow problem can be encountered with all three operation systems. Depending on the calculation mode, FURDEV will suggest increasing the flow rate and/or decreasing the length of the furrow.

#### *Advance time problem with cutback system*

In Calculation Modes 1 and 2, FURDEV calculates the required advance time as a function of the user-specified advance ratio and the required intake opportunity time. You can satisfy the advance time requirement by selecting the appropriate value of flow rate in Mode 1 or furrow length in Mode 2.

In Calculation Mode 1, the advance time associated with the maximum non-erosive flow rate can be longer than that of the required advance time. In such a situation, the required advance time cannot be achieved without using a flow rate that is greater than the maximum non-erosive one. This is clearly unacceptable. The only way out of this problem is to reduce the furrow length and/or increase the advance ratio. In addition, there are cases in which the flow rate corresponding to the required advance time is less than the minimum flow rate required to advance to the downstream end of the furrow. When this happens, FURDEV will advise you to increase the furrow length and/or the advance ratio.

In Calculation Mode 2 – with some parameter and variable combinations – it is possible that the required advance time is greater than the advance time that corresponds to the maximum length to which the user-specified flow rate can advance. To overcome this difficulty, FURDEV will recommend that you increase the flow rate and/or decreasing the advance ratio.

#### *Cutoff time problem*

In Calculation Modes 1, 2 and 3, the cutoff time is calculated so that the minimum infiltrated amount is equal to the required amount. In Mode 4, the cutoff time is an input. If the user-specified cutoff time is too short, it is possible that the calculated advance time will exceed it. This is a situation that cannot be handled by FURDEV. When such a problem is encountered, the screen message will recommend decreasing the furrow length and/or increasing the flow rate, and/or increasing the cutoff time.

#### *Check furrow cross-section*

The message is generated based on an assumed furrow depth of 20 cm and a ridge width of 20 cm. For the given side slope of a triangular furrow of 1.5:1, the furrow spacing should then be  $2 \times 1.5 \times 20 + 20 = 80$  cm. If your spacing input

value is less than this 80 cm, this message appears on the monitor, together with the results of the simulation.

#### *Spacing and section are incompatible*

This message deals with the same geometrical check as explained above, but instead of the assumed furrow depth, the actual flow depth calculated in the simulations is used, considering no freeboard. The width of the ridge is still assumed to be 20 cm. If the input furrow spacing is less than the calculated required minimum one, the message that will appear on the monitor is: spacing and section are incompatible, meaning physically impossible. Therefore, you will get no results and will have to change one of the input values.

#### *Calculated flow velocity is more than maximum permissible*

The meaning of this message is obvious. The flow velocity calculated by the program is more than the permissible value of the input field parameters. Nevertheless, the calculation results will show up on the screen. The idea is that you will have to decide whether you find the high velocity acceptable or not.

## 7.5 Assumptions and limitations

The FURDEV program is based on the volume balance method, which is explained in detail in Appendix B. The main difference between furrows and basins or borders is that the geometry of their cross-sections is different and that therefore the infiltration process and the flow process also differ. In basins and borders, it is generally assumed that the infiltration is one-dimensional in the vertical downward direction, whereas in furrows water infiltrates over the entire wetted perimeter in the furrow and should therefore be characterised as a two-dimensional process.

The volume balance method calculates the propagation of the wetting front along the furrow during the advance phase. Algebraic equations are used to simulate the ponding, depletion and recession phases. Implicit assumptions for the modelling of the advance phase are as follows:

- The furrow slope is greater than zero. The field can have a minor cross slope as long as the slope in the furrow is constant.
- The cutoff time is always greater than the advance time. This limitation is introduced to make sure that advance and recession do not occur simultaneously; a situation that the volume balance model cannot handle. During the advance time, the inflow is constant.
- The furrow is free-draining at the end. FURDEV is not able to calculate the advance and recession curve for closed-end conditions. To reduce losses and in particular runoff losses, the program can be run in the operation modes *Cutback flow* and *Tailwater reuse*. FURDEV does not compute how the

runoff water re-enters the system. That will be determined by local conditions. In the *Tailwater reuse* mode, it is assumed that a certain fraction of the runoff water, to be specified by the user, is reused within the same furrow, or in a downstream furrow. In the *Cutback* mode, it is assumed that, when water reaches the end of the furrow, the inflow is reduced to a value less than the inflow rate during the advance phase. Before and after cutback, the flow rate is constant.

Additional assumptions involved in the simulation of depletion and recession phases are discussed in detail in Appendix B. Other general theoretical assumptions are that the infiltration can be described by the modified Kostiaikov-Lewis infiltration function, and that the infiltration parameters have to be derived from a furrow used as infiltrometer. Further, the water depth at the upper boundary of the furrow can be described with Manning's equation. The geometry of the cross-section of the furrow (triangular, parabolic or, trapezoidal) is simulated in the program by a power law for the wetted cross-section and the wetted perimeter: the upper boundary of the inflow is the maximum non-erosive flow rate, which can be calculated with the method developed by Hart et al. (1980); and the minimum flow rate is determined by advance considerations (Hart et al. 1980).

Apart from these more theoretical assumptions related to the algorithm and its solutions (ie, accepting the model as it is), the following practical conditions are assumed for the use of FURDEV:

- The inflow rate is constant during the entire application time, apart of course from a possible reduction in case of a cutback operation.
- The soil is homogeneous throughout the length of the furrow.
- The roughness coefficient is constant in space and time.
- The cross-section is constant over the furrow length.
- The cutoff time is always greater than advance time.
- The furrow slope is uniform along the length.

The simulation results obtained with FURDEV will be much in line with field observations, provided that the field conditions match the assumptions made in the program and that the consequent limitations are respected. As stated in the other programs, FURDEV only deals with the technical and hydraulic aspects of furrow irrigation. The program should therefore be regarded as an aid in the design, operation, and evaluation. In addition to the findings of the program, final decisions in the field will be affected by agricultural, economic and social considerations.

## 7.6 Program usage

The following 10 steps are important in the usage of the FURDEV program.

1. Start the SURDEV package. Select FURDEV from the main menu of SURDEV.
2. If you want to use an existing file, retrieve it with the *Load* command under the *Files* menu. If you want to make a new file, go straight to the *Calculation* menu bypassing the *Files* menu, and you will get a set of default data.
3. If you want to simulate *Cutback flow* or *Reuse*, go to the *Operation* menu and select the operation mode to work with. The program default operation mode is *Fixed inflow*.
4. Select the *Units* menu only when you want to work with units other than the default units.
5. The default infiltration mode is the "Modified SCS families". If you want to work with another infiltration mode, go to the *Parameters* menu and select the *Infiltration* menu.
6. The program default geometry is the triangular cross-section under the heading cross-sectional shapes. Changes can be made under *Parameters* and *Geometry*.
7. Select a mode to work in from the *Calculation* menu. Most work will be done in Modes 3 and/or 4. Less experienced users can start in Mode 1 or 2 to get a first estimate of the flow rate or field dimensions, respectively, and then continue in Mode 3 and/or 4. Mode 4 can be used to evaluate an existing situation or to do sensitivity analyses.
8. You can specify field parameters and decision variables in the input window, after which the program can be run by pressing the key [F2].
9. You can view the results of each run in tabular form in the output window, or in graphical form by pressing [F3]. You can save the results of one simulation run (output and input in one file) in a separate file or append them to earlier runs in an existing file by pressing [F4].
10. Select *Files* and *View/Print* from the main menu to see what has been done and/or to print a file directly, or convert it to a print file for a word-processor program, or convert it to a file to be imported into a spreadsheet program where you can make your own graphs.

## 7.7 Sample problems

In most cases, users will not be satisfied with a solution obtained after one run, and will usually do a number of runs to get an acceptable solution. Two simple examples are given to illustrate this procedure. More elaborate problems can be found in Chapter 8, Section 3.

### 7.7.1 Determine furrow length

A design combination is to be developed for a fixed-flow furrow irrigation system in which the available inflow rate into the furrow is fixed at 1 l/s. The soil is silty-loam and can be classified by the Intake Family # 0.6. The value of the flow resistance is fixed at 0.04. The net irrigation requirement is 100 mm. The furrows have a triangular cross-section with a side slope of 1:1, a slope of 0.008, and a spacing of 75 cm. Determine the furrow length in such a way that the application efficiency is at least 70 per cent and the cutoff time has a practical value. The maximum feasible furrow length is 600 m in the direction of the main field slope.

1. We want to make a new file, and therefore do not need to use the *Files* sub-menu. Note, the default operation, units, and parameter modes must be used in this problem, so you can go directly to the *Calculation* menu and select Mode 2: Furrow length. Enter the above values in the two input windows and make a run ([F2]).
2. The results of this run (Table 7.5, Run 1) show that, with an available flow rate of 1 l/s, a furrow 338 m long can be irrigated with an application efficiency of 71 per cent. This requires a cutoff time of 596 minutes. The corresponding uniformity coefficient is 93 per cent and the distribution uniformity is 82 per cent. From these values, it will be clear that a furrow length of 600 m is too long for an application efficiency of 70 per cent. Suppose the field can be divided into two parts, each 300 m long. Run FURDEV in Mode 3 to see the effect when the furrow length is reduced to 300 m.
3. The results of this run (Table 7.5, Run 2) show that a slightly shorter furrow reduces the application efficiency from 71 to 70 per cent, which is acceptable. The cutoff time, however, has an impractical value (536 min). Run FURDEV in Mode 4 to see the effect when the cutoff time is reduced from 536 to 480 minutes.
4. The results of this run (Table 7.5, Run 3) show that this reduction in cutoff time results in a slight under-irrigation: the minimum infiltrated depth is now 90 mm instead of 100 mm, while the uniformity coefficient is 95 per cent. The application efficiency has increased to 77 per cent and the distribution uniformity is 86 per cent. Over the lower 75 m of the furrow, the average depth infiltrated would be 4 mm less than that required. The upper 225 m of the furrow would receive an average over-irrigation depth of 8 mm. These results are acceptable.

Table 7.5 can be made with FURDEV. The procedure is as follows. Save Run 1 with [F4] and prescribe a particular file name (EXAMPLE1). FURDEV automatically adds the extension .FDR to this file name. Save Runs 2 and 3 with [F4] under the same file name using the *Append* option. Go back to the main



Table 7.5 Furdev program for furrow irrigation (Filename: EXAMPLE1)

Run no.		1	2	3
Type of system		1	1	1
Calculation mode		2	3	4
<hr/>				
Input data	Units			
Flow rate	l/s	1	1	1
Length	m	—	300	300
Cutoff time	min	—	—	480
Required depth	min	100	100	100
Flow resistance	—	0.04	0.04	0.04
Furrow slope	m/m	0.008	0.008	0.008
Furrow spacing	m	0.75	0.75	0.75
Maximum velocity	m/min	13.8	13.8	13.8
Side slope	—	1	1	1
Intake family	—	0.6	0.6	0.6
<hr/>				
Output data				
Flow rate	l/s	—	—	—
Length	m	338	—	—
Cutoff time	min	596	536	—
Application eff.	%	71	70	77
Storage eff.	%	100	100	99
Uniform. coeff.	%	93	95	95
Distrib. unif.	%	82	87	86
Deep perc. ratio	%	16	10	5
Runoff ratio	%	14	20	18
Advance time	min	226	163	163
Depletion time	min	602	541	485
Recession time	min	647	584	528
Opportunity time	min	421	421	365
Avg. inf. depth	mm	122	115	105
Max. inf. depth	mm	131	121	111
Min. inf. depth	mm	100	100	90
Surface runoff	mm	19	28	23
Over-irr.	mm	22	15	8
Under-irr.	mm	0	0	4
Over-irr. Length	m	338	300	225
Under-irr. Length	m	0	0	75

menu, then to the *Files* menu and select *View*. See the results and select [F5] (*Print/Save*) and then use the option *Text file*. FURDEV now automatically adds the extension .TXT to the file name EXAMPLE1. If you now go out of FURDEV, you can load the results in a word processing program by retrieving the file EXAMPLE1.TXT.

The above problem uses *the Fixed flow* operation mode. Nevertheless, a similar line of reasoning can be employed in the use of the other two operation modes.

### 7.7.2 Determine flow rate

A design is to be made for an existing field with 400 m long furrows. The soil is silty-loam and can be classified by the Intake Family # 0.6. The net irrigation requirement is 100 mm. The furrows have a triangular side slope of 1:1, a slope of 0.008, and a spacing of 75 cm. Determine the flow rate in such a way that the application efficiency is at least 70 per cent and the cutoff time is not more than 420 minutes.

1. Go to the *Calculation* menu and select Mode 1: *Flow rate*. Enter the above values in the two input windows and make a run. Save the results as **EXAMPLE2**.
2. This run (Table 7.6, Run 1) shows that at a flow rate of 1.21 l/s this furrow can be irrigated with an application efficiency of 71 per cent. A cutoff time of 587 min will then be required, so, the cutoff time needs to be reduced. Run **FURDEV** in Mode 4 to see the effect when the cutoff time is reduced from 602 to 480 minutes.
3. The results of this run (Table 7.6, Run 2) show that, although the application efficiency has increased to 84 per cent, there is under-irrigation: the minimum infiltrated depth is 80 mm. Run **FURDEV** again in Mode 4 to see the effect when the flow rate is increased from 1.21 to 1.5 l/s.
4. From this run (Table 7.6, Run 3) you will see that there is now slight over-irrigation (the minimum infiltrated depth is 101 mm) and the application efficiency is reduced to 69. So, there is now scope to reduce the cutoff even further. Run **FURDEV** again in Mode 4 to see the effect when the cutoff time is reduced from 480 to 420 minutes;
5. Once again this run (Table 7.6, Run 4) will show that there is under-irrigation (the minimum infiltrated depth is 89 mm), while the uniformity coefficient is 95 per cent. The application efficiency is 78 per cent and the distribution uniformity is 86 per cent. Over the lower 117 m of the furrow, the average depth infiltrated would be 5 mm less than that required. The upper 283 m of the furrow would receive an average depth of 107 mm. These results are acceptable.

Table 7.6 was also made with **FURDEV**. Once you are familiar with the foregoing basic elements of working with the program, you can tackle more elaborate problems. Examples are presented in Chapter 8 and concern several sets of runs with which various relationships can be established. They not only illustrate the potential of **FURDEV**, but also provide you with a deeper insight into the complex nature of the furrow irrigation process.

Table 7.6 Furdev program for furrow irrigation (File name: EXAMPLE2)

Run no.		1	2	3	4
Type of system		1	1	1	1
Calculation mode		1	4	4	4
<hr/>					
Input data	Units				
Flow rate	l/s	—	1.21	1.5	1.5
Length	m	400	400	400	400
Cutoff time	min	—	480	480	420
Required depth	mm	100	100	100	100
Flow resistance	—	0.04	0.04	0.04	0.04
Furrow slope	m/m	0.008	0.008	0.008	0.008
Furrow spacing	m	0.75	0.75	0.75	0.75
Maximum velocity	m/min	13.8	13.8	13.8	13.8
Side slope	—	1	1	1	1
Intake family	—	0.6	0.6	0.6	0.6
<hr/>					
Output data					
Flow rate	l/s	1.21	—	—	—
Cutoff time	min	587	—	—	—
Application eff.	%	71	84	69	78
Storage eff.	%	100	97	100	99
Uniform. Coeff.	%	93	91	95	95
Distrib. Unif.	%	80	75	88	86
Deep perc. ratio	%	17	7	11	4
Runoff ratio	%	12	9	20	17
Advance time	min	243	243	157	157
Depletion time	min	594	486	486	426
Recession time	min	644	534	538	477
Opportunity time	min	401	291	381	320
Avg. inf. Depth	mm	125	106	115	104
Max. inf. Depth	mm	134	116	121	110
Min. inf. Depth	mm	100	80	101	89
Surface runoff	mm	17	10	29	22
Over-irr.	mm	25	12	15	7
Under-irr.	mm	0	9	0	5
Over-irr. Length	m	400	283	400	283
Under-irr. Length	m	0	117	0	117



## 8 Program applications

In this chapter, we present examples of design, operation and evaluation aspects pertaining to the three surface irrigation methods dealt with in this book. These aspects are discussed in three sections, one for each of the three methods, and can be read independently of each other. For instance, readers wishing to familiarise themselves with the various aspects of border irrigation can go directly to Section 8.2, or to Section 8.3 for furrow irrigation.

All examples given are stored on the accompanying SURDEV diskette. Their file names are mentioned in the text of this chapter. The user can opt to see how we made the applications or he can do it himself.

### 8.1 Level-basin irrigation

Level-basin irrigation design involves dealing with an optimum combination of design variables, namely, length, width, flow rate and cutoff time. As indicated in Chapter 3, the existing situation may place restrictions on one or more of these variables. The purpose of the design and the nature of the restrictions determine how one can use BASDEV to find an adequate solution. Two design examples are presented below: the first explains how to find the best possible flow rate for given and fixed dimensions (Section 8.1.1), and the second, how to find appropriate basin dimensions for a given flow rate (Section 8.1.2). The latter example also includes operational aspects. In Section 8.1.3, a field situation is presented in which all parameters are fixed and there is a clear field irrigation problem. We have analysed the problem and evaluated some options for improvement.

#### 8.1.1 Flow rate

A design is to be made for an existing basin of 50 by 30 m. The soil type is sandy loam and can be classified by the SCS family # 2.0. The flow resistance (broadcast small grains) can be taken as 0.15. The net irrigation requirement is 80 mm.

To judge the best flow rate, use the application efficiency. Select Mode 1 (*Flow rate*) from the *Calculation* menu immediately after starting BASDEV, to get a first approximation of the flow rate. The results are:  $Q = 40$  l/s;  $E_a = 0.70$ ;  $T_{co} = 71$  minutes; and  $T_a = 56$  minutes. To see whether a higher application efficiency can be achieved, continue with Mode 3 (*Cutoff time*) of the *Calculation* menu. Make consecutive runs with increasing  $Q$ -values until the cutoff time approximately equals the advance time; Table 8.1 shows that this

Table 8.1 Results of the trial runs for different flow rates (file DESIGN1A)

Q (l/s)	E <sub>a</sub> (%)	T <sub>co</sub> (min)	T <sub>a</sub> (min)
40	70	71	56
50	77	52	41
60	81	41	33
70	83	34	28
80	85	29	25
100	87	23	20
150	90	15	15

occurs at a Q-value of 150 l/s. This table shows that there is no optimum solution: the higher the flow rate the higher the application efficiency. The table also shows that at lower values of Q, an increase in Q causes a corresponding increase in E<sub>a</sub>, but at higher values of Q an increase affects E<sub>a</sub> to a lesser degree. This phenomenon is illustrated in Figure 8.1. There is also the practical side: the upper limit of the flow rate should be such that a farmer will be able to handle it. Suppose that the farmer can handle 80 l/s. The application efficiency would then be 85 %, the cutoff time (T<sub>co</sub>) 29 minutes and the advance time (T<sub>a</sub>) 25 minutes. This is the best result possible, provided the minimum infiltrated depth at the downstream end of the basin is equal to the required depth.

The next step is to ensure that the value of the cutoff time will be practical. Running BASDEV in Mode 3 will generally result in odd cutoff time values. Select Mode 4 (*Minimum infiltrated depth*) and change the cutoff time from 29.45 to 30 minutes. The minimum infiltrated depth will increase slightly from 80 to 82 mm and the application efficiency will decrease a little from 85 to 83 % (Run 1 in Table 8.2). This is still an acceptable design.

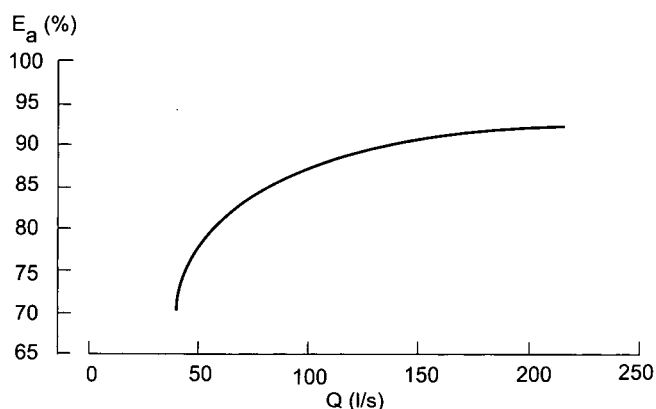
Figure 8.1 Relationship of flow rate Q to application efficiency E<sub>a</sub>

Table 8.2 Results of sensitivity runs (file DESIGN1B)

Run number	1	2	3	4	5
Calculation mode	4	4	4	4	4
INPUT PARAMETERS					
Cutoff time	30	30	30	30	30
Flow resistance	0.15	0.15	0.15	0.10	0.20
SCS #	2.0	3.0	1.5	2.0	2.0
OUTPUT PARAMETERS					
Application efficiency	83	83	83	83	83
Storage efficiency	100	99	100	100	100
Distribution uniformity	85	73	90	87	83
Minimum infiltrated depth	82	70	86	84	80
Maximum infiltrated depth	105	112	103	104	107
Average infiltrated depth	96	96	96	96	96
Over-irrigation depth	16	19	16	16	16
Under-irrigation depth	0	5	0	0	0
Over-irrigation length	50	43	50	50	50
Under-irrigation length	0	7	0	0	0

The last step is to make sensitivity analyses on the field parameters used in the design, ie, an intake family of # 2.0 and a flow resistance of 0.15. Table 8.2 shows the changes in the irrigation performance when the soil in the field appears to behave more like intake family # 3.0 (slightly more sandy) or intake family # 1.5 (slightly more loamy), or when the actual resistance appears to be 0.10 or 0.20. Table 8.2 shows that except for Run 2 (intake family # 3.0) all the other runs result in the same amount of over-irrigation (16 mm) over the full 50 m, but with slightly different distribution uniformities. For intake family # 3.0, there is more over-irrigation (19 mm), but at the downstream end of the basin now there is also under-irrigation: an average 5 mm over the lower 7 m and a minimum infiltrated depth of 70 mm at the downstream end of the basin. The conclusion is that this design is not very sensitive to changes in the assumed infiltration properties, while the effect of a different flow resistance on the irrigation performance is almost negligible. This picture may change, of course, if other combinations of input variables would be used.

### 8.1.2 Basin dimensions

A design is to be made for a situation where the available flow rate is fixed at 30 l/s. The soil type is silt and can be classified by the SCS family # 1.5. The crops are grown in rows in the direction of flow, which means that the value of the flow resistance can be taken as 0.20. The net irrigation requirement is 80 mm.

To ascertain the best basin dimensions, use the application efficiency again. Select Mode 2 (Dimensions) from the *Calculation* menu immediately after starting BASDEV, to get a first approximation of the basin dimensions. The results you will get are:  $L = W = 28$  m;  $E_a = 0.88$ ;  $T_{co} = 41$  minutes; and  $T_a = 25$  minutes.

The next step is to ensure that the basin dimensions will have practical values. Select Mode 3 (*Cutoff time*) and change the basin dimensions to 30 by 30 m. The advance time is now 30 min, the cutoff time 47 min and the application efficiency 86 % (Run 2 in Table 8.3).

The following step is to ensure that the cutoff time will have a practical value. Let us suppose in this case that the designer also allows some under-irrigation. Select Mode 4 (*Minimum infiltrated depth*) and make consecutive runs with decreasing  $T_{co}$  values till the cutoff time approximately equals the advance time. Runs 3 to 6 of Table 8.3 show that the application efficiency steadily increases from 89 to 100 %, whereas the storage efficiency and distribution uniformity steadily decrease owing to increasing under-irrigation. The relationships illustrated in Figure 8.2 clearly show that here the application efficiency is no longer a yardstick to judge the irrigation performance. It is now up to the designer to choose how much under-irrigation he allows to

Table 8.3 Results of the trial runs for different cutoff times (file DESIGN2)

Run number	1	2	3	4	5	6
Calculation mode	2	3	4	4	4	4
INPUT PARAMETERS						
Basin length	—	30	30	30	30	30
Basin width	—	30	30	30	30	30
Cutoff time	—	—	45	40	35	30
OUTPUT PARAMETERS						
Basin length	28	—	—	—	—	—
Basin width	28	—	—	—	—	—
Cutoff time	41	47	—	—	—	—
Application efficiency	88	86	89	96	100	100
Storage efficiency	—	—	100	96	87	75
Distribution uniformity	—	—	85	82	79	73
Minimum infiltrated depth	—	—	77	66	55	44
Maximum infiltrated depth	98	101	98	89	79	70
Average infiltrated depth	91	93	90	80	70	60
Over-irrigation depth	—	—	11	5	0	0
Under-irrigation depth	—	—	2	6	10	20
Over-irrigation length	—	—	27	17	0	0
Under-irrigation length	—	—	3	13	30	30
Advance time	25	30	30	30	30	30



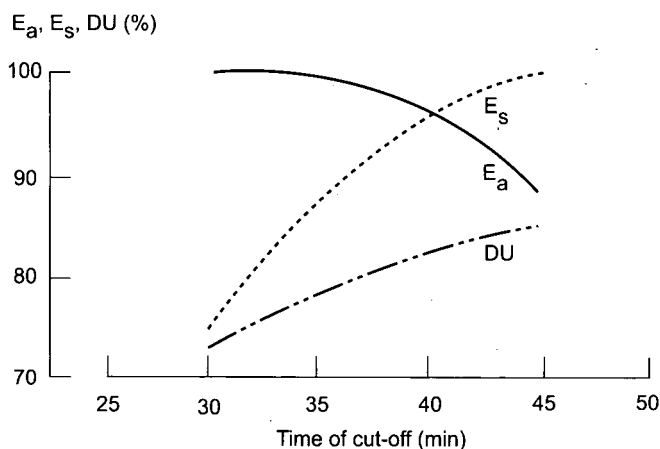


Figure 8.2 Relationships of cutoff time to application efficiency  $E_a$ , storage efficiency  $E_s$ , and distribution uniformity DU

occur in his design. Unfortunately, certain threshold values of the storage efficiency and distribution uniformity cannot be used for this purpose because they will have different values for different combinations of input parameters. Therefore, we propose that a certain percentage of the required depth, for instance 10 %, be allowed as average under-irrigation depth. If this percentage is adopted, Table 8.3 shows that a cutoff time of 40 min can be acceptable for the final design.

The previous two examples only show certain elements of the design procedure. There are no general and strict guidelines for all design situations. Each specific combination of parameters will have its own solution, which will depend on the prevailing objectives, practices, and so on. Nevertheless, the following guidelines can be formulated on how to use BASDEV in the design process:

- Run BASDEV in Modes 1 or 2 to get a first value of the flow rate or basin dimensions. If you have sufficient experience, start immediately in Mode 3.
- Proceed to Mode 3 and vary the flow rates or basin dimensions to see how the application efficiency varies accordingly. Determine the maximum flow rate a farmer can handle or the basin dimensions that are feasible, using the application efficiency as a yardstick. This gives the best design possible, provided the minimum infiltrated depth at the downstream end of the basin is equal to the required depth.
- Proceed to Mode 4 to make any necessary refinements to the cutoff time. If no under-irrigation is to occur in your design, the value of the cutoff time as obtained from Mode 3 will only need to be rounded off to the nearest practical value.
- If you allow under-irrigation in your design, reduce the cutoff time in a stepwise manner till it approximately equals the advance time. Determine

the minimum cutoff time using a certain percentage of the required depth to be allowed as average under-irrigation depth as a yardstick.

- Finally, do sensitivity analyses of the field parameters (also in Mode 4) to see if the selected design should be retained.

### 8.1.3 Evaluation of an existing situation

In existing irrigation schemes, all field parameters and decision variables are fixed. Basin dimensions are laid out in the field and flow rate and cutoff time are determined by the main system supplies and the subsequent water distribution practices in the tertiary unit. Mode 4 of BASDEV can then be used to assess the adequacy, efficiency, and uniformity of water application in the existing situation. If the performance proves to be unsatisfactory, suggestions for improvement can be evaluated with BASDEV.

Take the following irrigation situation of one farmer who irrigates 0.8 ha of land. Because of the local topography his irrigated land is laid out in two basins, both 80 m in length. The width of the basins, however, is different, Basin 1 being 40 m wide and Basin 2 being 60 m wide. There is a strict, rotational water distribution system within the tertiary unit. The farmer has a turn of 216 minutes once a week, during which he receives water at a flow rate of 50 l/s.

The above data are based on the following situation. The size of the tertiary unit is 34 ha and the net water requirement of the crop is 10 mm/d, or 1.16 l/s ha. This means that the net flow rate for 34 ha is 40 l/s. If we assume an overall efficiency of some 75 %, then the gross flow rate is about 50 l/s. The area-based rotation roster allocates the farmers 153 hours a week (168 hours minus 15 hours for transitions). Thus, individual turns are based on an allocated time of  $153/34 = 4.5$  hours = 270 minutes per ha. So the time available for our farmer with his 0.8 ha, is  $0.8 \times 270 = 216$  minutes.

Assume a modified SCS intake family # 1.0 to describe the soil and a flow resistance of  $n = 0.20$ . With the daily net requirement of 10 mm and the weekly schedule,  $D_{\text{req}} = 70$  mm. The farmer irrigates his two basins one after the other, using the full available flow rate of 50 l/s. He divides his application time proportional to the basin widths – 86 minutes for the 40-metre-wide basin and 130 minutes for the 60-metre-wide basin. He is unhappy with the situation because he observes a clear yield reduction at the end of the first basin and the waterfront does not usually even reach the end of the second basin.

We used BASDEV to evaluate the existing situation and to look for ways of improving it. Run 1 of Table 8.4 shows the existing situation for Basin 1. There is considerable under-irrigation in this basin: an average 11 mm under-irrigation over the lower 21 m of the basin and a minimum infiltrated depth of 47 mm at the downstream end of the basin. The advance time is 101 min-

Table 8.4 Results of the trial runs for improving the existing situation (file BASIN 1)

Run number	1	2	3
Calculation mode	4	4	4
INPUT PARAMETERS			
Flow rate	50	50	50
Basin length	80	80	80
Basin width	40	40	40
Cutoff time	86	86	96
Required depth	70	70	70
Flow resistance	0.20	0.10	0.10
SCS #	1.0	1.0	1.0
OUTPUT PARAMETERS			
Application efficiency	83	85	78
Storage efficiency	96	98	100
Distribution uniformity	58	67	72
Minimum infiltrated depth	47	54	64
Maximum infiltrated depth	99	95	104
Average infiltrated depth	81	81	90
Over-irrigation depth	18	13	22
Under-irrigation depth	11	8	3
Over-irrigation length	59	62	74
Under-irrigation length	21	18	6
Advance time	101	81	81
Recession time	154	145	145

utes, which is longer than the cutoff time (86 minutes). The flow is apparently sufficient to reach the end of the basin but not enough to avoid under-irrigation there. The conclusion is that the farmer is indeed the victim of the existing situation and that he cannot do much to improve it without effecting drastic changes in the design or operation of the irrigation system.

Now let us look for ways of improving the situation in Basin 1. Because it suffers from under-irrigation at the far end, the first choice that comes to mind is either to increase the flow rate or to make the basins shorter. Increasing the flow rate is not a real option in this case, because a higher flow rate is not available. Making the basins narrower, so that the unit flow rate will be higher, is not a logical practical solution either. A better idea may be for the farmer to grow another crop and improve his land levelling. If he does this, we can assume a flow resistance of  $n = 0.10$ . Run 2 of Table 8.4 shows what will be the effect of this land levelling on the irrigation performance: a significant increase in the minimum infiltrated depth and a slight reduction in both the average under-irrigation depth and the under-irrigation length. Remember, in the case of under-irrigation the application efficiency is no longer a yardstick for irrigation performance (see also Section 8.1.2).

Next, we used BASDEV to evaluate the existing situation in Basin 2. BASDEV gave no results at all, except for an error message. If the cutoff time is increased to 152 minutes (Run 1 of Table 8.5) it becomes clear why BASDEV gave no results at all for a cut off time of 130 min. Even at 152 minutes, there is still under-irrigation: 21 mm over a length of 16 m and a minimum infiltrated depth of 25 mm only. The required advance time is 191 minutes, meaning that at the time of cutoff, the waterfront will still not have reached the end of the field ( $T_{co} < T_a$ ). The situation will be even worse for the actual cutoff time of 130 minutes.

The available cutoff time, however, remains 130 min. We reduced the basin length in a trial-and-error fashion to obtain a result with BASDEV. Run 2 of Table 8.5 shows results for a reduced basin length of 65 m: the minimum infiltrated depth will be 61 mm, the application efficiency 70 % and the advance time 123 min. This is not a proper solution because the last 15 m of the basin (an area of 15 x 60 m) would not be irrigated. An alternative idea may be for the farmer to grow another crop and improve his land levelling, as was proposed for Basin 1. Run 3 of Table 8.5 shows what will be the effect of this land levelling on the irrigation performance: the full area can now be irrigated, but the minimum infiltrated depth is very low and the under-irrigation is too high.

Table 8.5 Results of the trial runs for improving the existing situation (file BASIN 2)

Run number	1	2	3	4	5	6	7	8
Calculation mode	4	4	4	4	4	4	4	4
<b>INPUT PARAMETERS</b>								
Flow rate	50	50	50	50	50	50	50	50
Basin length	80	65	80	60	60	60	60	80
Basin width	60	60	60	40	40	40	80	60
Cutoff time	152	130	130	65	65	60	130	260
Required depth	70	70	70	70	70	70	70	140
Flow resistance	0.20	0.20	0.10	0.20	0.10	0.10	0.10	0.20
SCS #	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
<b>OUTPUT PARAMETERS</b>								
Application efficiency	69	70	78	85	86	91	79	85
Storage efficiency	94	100	91	99	100	98	92	98
Distribution uniformity	26	61	16	76	81	79	25	69
Minimum infiltrated depth	25	61	13	62	66	59	20	112
Maximum infiltrated depth	125	120	107	93	90	84	105	186
Average infiltrated depth	95	100	81	81	81	75	81	163
Over-irrigation depth	36	33	25	14	13	9	23	30
Under-irrigation depth	21	4	24	4	2	5	21	13
Over-irrigation length	64	60	58	51	55	44	44	66
Under-irrigation length	16	5	22	9	5	16	16	14
Advance time	191	123	163	62	48	48	149	191
Recession time	212	200	172	140	134	122	165	374

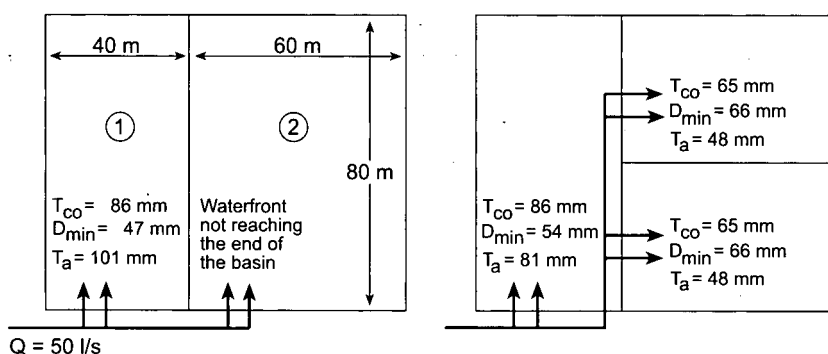


Figure 8.3 Existing and improved situation of basin irrigation

A much better solution would be to re-route the supply ditch for Basin 2 along the joint border of the two basins and then to divide Basin 2 in half. Then there would be two basins of 40 m x 60 m instead of one basin of 60 m x 80 m. Each of these basins would receive an irrigation turn of 65 minutes, one after the other (see Figure 8.3). Run 4 of Table 8.5 shows that this would give both basins a minimum infiltrated depth of 62 mm with a slight, but acceptable under-irrigation. This is a practical and easy solution for the farmer. A further refinement could be to make the flow resistance  $n = 0.10$ , as we suggested above (see Run 5). The result for the two new basins would then be even better, and a somewhat shorter cutoff time of 60 minutes can be considered (see Run 6). The remaining 2 x 5 minutes could then be used to irrigate Basin 1 a bit longer, improving the irrigation performance even further (see Run 3 of Table 8.4).

Finally, let us examine the possibilities for improvement if the farmer prefers not to divide Basin 2 in half. He could, for instance, try to irrigate this basin from the side, with  $L = 60$  m,  $W = 80$  m, and  $T_{co} = 130$  minutes. Run 7 of Table 8.5 shows that the resulting performance would still be very poor (see Run 7). A better alternative would be to consider changing the required depth for the existing basin ( $L = 80$  m and  $W = 60$  m), which could require a supply of, say,  $D_{req} = 140$  mm once every two weeks. The available cutoff time would then be twice as long. Run 8 of Table 8.5 shows the results: a minimum infiltrated depth of 112 mm (with a slight under-irrigation), an application efficiency of 85 %, and an advance time of 191 minutes. Note, the solution presented in Run 6 of Table 8.5 still gives a better irrigation performance.

There are no general guidelines for evaluating an existing situation. Some of the simulated options may not be realistic for practical application as they depend on the given situation or on the farmer's objectives and priorities. What the above does show is that BASDEV is an easy and effective tool for analysing the situation and predicting the consequences of various solutions. Moreover, it could indeed show that the farmer is not to blame for poor irri-

gation practices and that it is impossible for him to do better under the given circumstances.

## 8.2 Border irrigation

As in level-basin irrigation, design issues in border irrigation generally have to do with finding the optimum combination of design variables, notably, the length, flow rate, and cutoff time. Another major variable, however, that does not appear in basin irrigation, is the slope of the field. Consequently, in border irrigation, there will be surface runoff. As was mentioned in Chapter 3, the existing situation may place restrictions on one or more of these variables. The purpose of the design and the nature of the restrictions determine how one can use BORDEV to find an adequate solution to a border irrigation problem.

In Sections 8.2.1 and 8.2.2, we shall consider two examples of a border irrigation situation. The first example shows how to find the best flow rate for given and fixed border dimensions and, the second example, how to find an adequate border length for a given flow rate. Section 8.2.3 contains an analysis of the relation between length and flow rate. Section 8.2.4 discusses some of the operational aspects to improve efficiency in a given situation, including how to apply cutback and reuse procedures. Finally, Section 8.2.5 deals with field slope, a typical aspect of border irrigation as compared to level-basin irrigation.

### 8.2.1 Flow rate

A design is to be made for an existing border of 150 by 20 m. The soil type is coarse sandy-loam and can be classified by the soil intake family # 1.0. The net irrigation requirement is 80 mm. The field slope is 0.005 in the direction of the length of the border. The flow resistance (broadcast small grains) can be taken as 0.15.

To judge the best flow rate, use the application efficiency. Select Mode 1 (*Flow rate*) from the *Calculation* menu immediately after starting BORDEV, to get a first approximation of the flow rate. Remember that the default operation system is fixed flow. The results are  $Q = 39.8$  l/s with an  $E_a$  of 66 %. The surface runoff (SRR) is 16 % and the deep percolation ratio (DPR) is 18 %. Together this is 34 %, so that  $E_a = 100 - 34 = 66$  %. To see how the flow rate influences the application efficiency, continue with Mode 3 (*Cutoff time*) of the *Calculation* menu. Make consecutive runs with varying  $Q$ -values, ie, 30, 35, 40, 45, 50, and 60 l/s. Table 8.6 shows that a maximum application efficiency  $E_a = 66$  % is obtained with  $Q = 40$  l/s, whereby the SRR equals the DPR (for  $Q < 40$  l/s,  $SRR < DPR$ ; for  $Q > 40$  l/s,  $SRR > DPR$ ). Remember that the sum of  $E_a$ , SRR, and DPR is always 100 %. Therefore,  $E_a$  is highest when  $SRR +$

Table 8.6 Determination of optimum border flow rate (file FIG84)

Run number	1	2	3	4	5	6
Calculation mode	3	3	3	3	3	3
INPUT PARAMETERS						
Flow rate	30	35	40	45	50	60
Border length	150	150	150	150	150	150
Border width	20	20	20	20	20	20
OUTPUT PARAMETERS						
Cutoff time	220	176	152	137	126	113
Application efficiency	61	65	66	65	63	59
Uniformity coefficient	87	89	91	93	94	96
Distribution uniformity	64	73	78	82	86	90
Minimum infiltrated depth	80	80	80	80	80	80
Maximum infiltrated depth	142	124	113	105	100	93
Average infiltrated depth	124	110	102	97	94	89
Deep percolation ratio	33	24	18	14	11	7
Surface runoff ratio	6	11	16	21	26	34

DPR is lowest. This phenomenon is illustrated in Figure 8.4. Note, this result differs from the one in Section 8.1.1 for level basins. Contrary to basins, there is an optimum flow rate for borders, one at which the application efficiency is

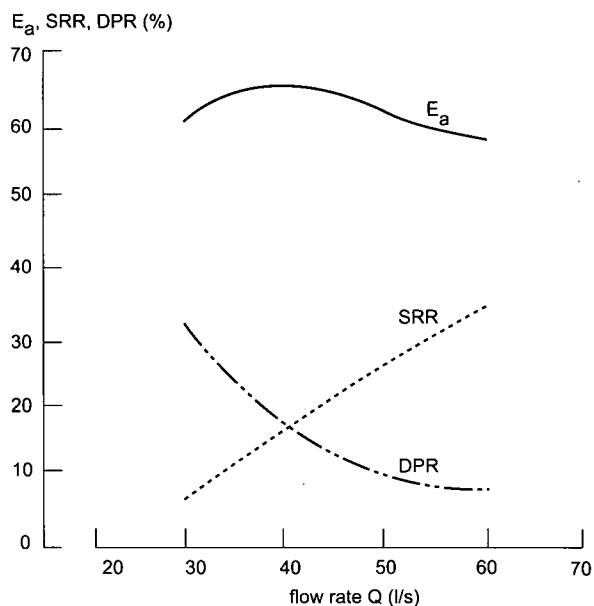


Figure 8.4 Relation of flow rate  $Q$  to application efficiency  $E_a$ , surface runoff ratio (SRR) and deep percolation ratio (DPR) for a border length  $L = 150$  m

at its highest. For this flow rate, the SRR and DPR are equal. This is the best result possible provided the minimum infiltrated depth at the downstream end of the border is equal to the required depth. The results of Mode 1 with which we started this design procedure ( $Q = 39.8$  l/s) gave almost the optimum flow rate. Note, this will not always be the case; it depends on the specific combination of selected input parameters.

The next step is to ensure that the cutoff time will have a practical value. Suppose that in this case the designer also allows some under-irrigation. Select Mode 4 (*Minimum infiltrated depth*) and make consecutive runs with decreasing  $T_{co}$  values till the cutoff time approximately equals the advance time. Runs 3 to 8 of Table 8.7 show that the application efficiency steadily increases from 67 to 91 %, whereas the storage efficiency and distribution uni-

Table 8.7 Results of the trial runs for different cutoff times (file DESIGN1)

Run number	1	2	3	4	5	6	7	8
Calculation mode	1	3	4	4	4	4	4	4
<b>INPUT PARAMETERS</b>								
Flow rate	—	40	40	40	40	40	40	40
Border length	150	150	150	150	150	150	150	150
Border width	20	20	20	20	20	20	20	20
Cutoff time	—	—	150	140	130	120	110	100
Required depth	80	80	80	80	80	80	80	80
Flow resistance	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Bed slope	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
SCS #	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
<b>OUTPUT PARAMETERS</b>								
Flow rate	39.8	—	—	—	—	—	—	—
Cutoff time	153	152	—	—	—	—	—	—
Application efficiency	66	66	67	71	76	81	86	91
Storage efficiency	100	100	100	100	98	97	94	91
Uniformity coefficient	91	91	91	91	90	89	88	87
Distribution uniformity	78	78	78	76	74	72	69	65
Deep percolation ratio	19	18	18	15	12	9	6	3
Surface runoff ratio	16	16	16	14	12	10	8	6
Minimum infiltrated depth	80	80	79	73	68	62	56	49
Maximum infiltrated depth	113	113	112	107	102	97	92	87
Average infiltrated depth	103	102	101	96	91	86	81	75
Over-irrigation depth	23	22	22	19	16	12	9	5
Under-irrigation depth	0	0	1	3	6	9	11	13
Over-irrigation length	150	150	144	131	119	106	88	69
Under-irrigation length	0	0	6	19	31	44	62	81
Advance time	99	98	98	98	98	98	98	98
Recession time	212	211	209	198	187	177	166	155



formity steadily decrease as a result of increasing under-irrigation. A similar relationship between these performance indicators exists as was indicated in Figure 8.2. It will be clear that in these cases the application efficiency is no longer a yardstick to judge the irrigation performance and that how much under-irrigation allowed to occur will be up to the designer. Certain threshold values of the storage efficiency and distribution uniformity unfortunately cannot be used for this purpose because they will have different values for different combinations of input parameters. We therefore propose using a certain percentage of the required depth, for instance 10 %, to be allowed as average under-irrigation depth. If this percentage is adopted Table 8.7 shows that you will get a cutoff time of 120 min that is acceptable for the final design.

### 8.2.2 Border length

A design is to be made for a situation where the available flow rate is fixed at 25 l/s. The soil type is moderately fine silty-loam and can be classified as soil intake family # 0.6. The net irrigation requirement is 75 mm. The field slope is 0.001 in the direction of the length of the border. The flow resistance (broadcast small grains) can be taken as 0.15.

To judge the best border dimensions, here again, use the application efficiency. Select Mode 2 (*Dimensions*) from the *Calculation* menu immediately after starting BORDEV, to get a first approximation of the border dimensions. Remember that the default operation system is fixed flow. The results are  $L = 176$  m,  $W = 18$  m, with an  $E_a$  of 66 % (Run 1 in Table 8.8). The SRR is 16 % and the DPR is 18 %, which are virtually equal indicating almost optimum conditions.

The second step is to ensure that the border dimensions will have practical values. Select Mode 3 (*Cutoff time*) and change the border dimensions to 170 m by 18 m. The advance time is now 180 min, the cutoff time is 233 min, and the application efficiency is 66 % (Run 2 in Table 8.8).

The following step is to ensure that the cutoff time will have a practical value. Running BORDEV in Mode 3 will generally result in odd values for the cutoff time. Select Mode 4 (*Minimum infiltrated depth*) and change the cutoff time from 233 to 240 min (= 4 hours). The minimum infiltrated depth will then slightly increase from 75 to 77 mm and the application efficiency will decrease a little from 66 to 64 % (Run 3 in Table 8.8). This is still an acceptable design.

The last step is to make sensitivity analyses on the field parameters used in the design, ie, an intake family of # 0.6 and a flow resistance of 0.15. Table 8.8 shows the changes in the irrigation performance when in the field the soil appears to behave more like intake family # 0.5 (fine silty-loam) or intake family # 0.7 (course silty-loam), or when the actual resistance appears to be 0.10 or 0.20.

Table 8.8 Results of design border length and sensitivity runs (file DESIGN2)

Run number	1	2	3	4	5	6	7
Calculation mode	2	3	4	4	4	4	4
<b>INPUT PARAMETERS</b>							
Flow rate	25	25	25	25	25	25	25
Border length	—	170	170	170	170	170	170
Border width	—	18	18	18	18	18	18
Cutoff time	—	—	240	240	240	240	240
Required depth	75	75	75	75	75	75	75
Flow resistance	0.15	0.15	0.15	0.15	0.15	0.10	0.20
Bed slope	0.001	0.001	0.001	0.001	0.001	0.001	0.001
SCS #	0.6	0.6	0.6	0.5	0.7	0.6	0.6
<b>OUTPUT PARAMETERS</b>							
Border length	176	—	—	—	—	—	—
Border width	18	—	—	—	—	—	—
Cutoff time	236	233	—	—	—	—	—
Application efficiency	66	66	64	64	64	64	64
Storage efficiency	100	100	100	100	100	100	100
Uniformity coefficient	91	92	92	94	89	92	91
Distribution uniformity	78	79	80	86	71	81	78
Deep percolation ratio	18	17	19	10	26	17	20
Surface runoff ratio	16	17	18	26	10	20	16
Minimum infiltrated depth	75	75	77	74	76	77	78
Maximum infiltrated depth	106	105	106	92	120	103	109
Average infiltrated depth <sup>96</sup>	95	97	97	87	106	95	99
Over-irrigation depth	21	20	22	12	31	20	24
Under-irrigation depth	0	0	0	0	0	0	0
Over-irrigation length	176	170	170	163	170	170	170
Under-irrigation length	0	0	0	0	0	0	0
Advance time	186	180	180	160	205	154	202
Recession time	368	362	370	380	361	342	394

Runs 4 to 7 in Table 8.8 show that the variation in infiltration and flow resistance properties results in significantly different amounts of over-irrigation and corresponding deep percolation ratios. The variations in the latter are counterbalanced by the surface runoff ratios: the sum of both is almost constant. This is the reason that the overall application efficiencies hardly change in value. Table 8.8 also shows that there is no measurable amount of under-irrigation. The conclusion is that this design is not very sensitive to changes in the assumed infiltration properties, while the effect of a different flow resistance is almost negligible on the irrigation performance. This picture may change, of course, if other combinations of input variables would be used.

The first step yielded a border length of 176 m. Suppose that this length is not feasible in the overall layout, then step 2 of the design procedure would be to run BORDEV in Mode 3 for different border lengths to see how the border

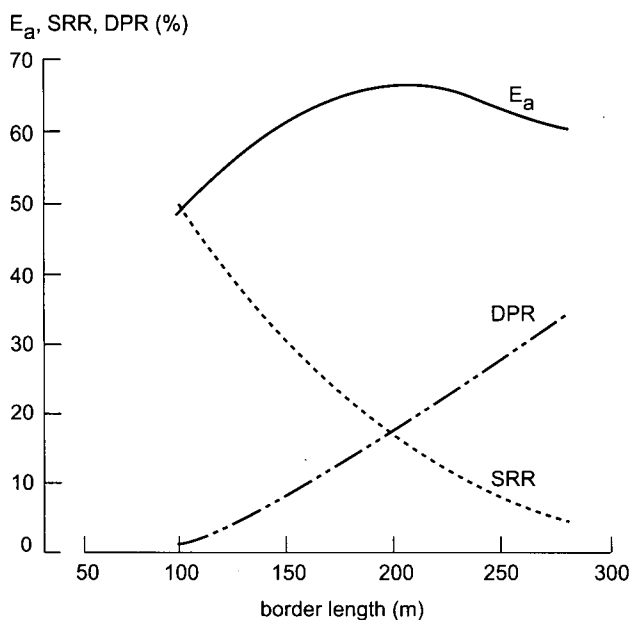


Figure 8.5 Relation of border length  $L$  to application efficiency  $E_a$ , surface runoff ratio SRR and deep percolation ratio DPR

length influences the application efficiency. We have done this and the results are shown in Figure 8.5. It shows that the application efficiency will be more than 60 % for border lengths ranging between 130 and 240 m. So it will make not much difference in the irrigation performance whether a border length of 150 m or one of 200 m is adopted in the final design. Figure 8.5 also shows that the optimum application efficiency is obtained where the surface runoff ratio equals the deep percolation ratio.

The previous two examples only showed certain elements of the design procedure. There are no general and strict guidelines for all design situations. Each specific combination of parameters will have its own solution, which will depend on the prevailing objectives, practices, and so on. Nevertheless, the following guidelines can be formulated on how to use BORDEV in the design process:

- Run BORDEV in Modes 1 or 2 to get a first value on the flow rate or the border dimensions. If you have sufficient experience, start immediately in Mode 3.
- Proceed to Mode 3 and vary the flow rates or border dimensions to see how the application efficiency varies accordingly. The maximum application efficiency is obtained when the surface runoff ratio equals the deep percolation ratio. Select flow rate and/or border dimensions that are feasible. This gives the best design possible provided the minimum infiltrated depth at the downstream end of the border is equal to the required depth.

- Proceed to Mode 4 to make refinements to the cutoff time. If you don't allow under-irrigation to occur in your design, the value of the cutoff time you obtained from Mode 3 will only need to be rounded off to the nearest practical value.
- If you allow under-irrigation in your design, reduce the cutoff time in a stepwise manner till it approximately equals the advance time. Determine the minimum cutoff time using a certain percentage of the required depth to be allowed as average under-irrigation depth as a yardstick.
- Finally, do sensitivity analyses of the field parameters (also in Mode 4) to see if the selected design should be retained.

### 8.2.3 Combinations of border length and flow rate

In the above two design examples, we have assumed that either the border dimensions or the flow rate are fixed beforehand. If both the border length and the flow rate can vary within certain limits, the following slightly adjusted procedure can be used. Determine the optimum flow rate as was done in the first section, ie, enter a length value in Mode 3 and vary the flow rate until  $SRR = DPR$  and  $E_a$  is maximum. Repeat this step for a range of border lengths. Table 8.9 shows the results for the same data as used in Section 8.2.1. This table shows that an irrigation efficiency around 66 % can be obtained for all combinations of border length and flow rate. Suppose a border length of 100 m and a flow rate of 27 l/s better fit in the overall layout of the irrigation system. Continue with Mode 4 to make refinements to the cutoff time and to do sensitivity analyses of the field parameters.

### 8.2.4 Operational aspects

The above examples illustrate how you arrive at an optimum design combination of width, length, and flow rate for given field parameters. In most cases, it is possible to obtain an irrigation efficiency of about 66 %, which is

Table 8.9 Optimum relationships between L and Q (file DESIGN3)

L (m)	Q (l/s)	$E_a$ (%)	$T_{co}$ (min)
50	13	67	154
75	20	66	151
100	27	66	150
125	34	66	149
150	41	66	149
175	49	66	145
200	57	65	143

reasonable, but one may wish to improve on it. There are three ways of doing this: reducing the cutoff time and accepting some under-irrigation at the far end of the field, applying cutback on the inflow, or reusing the tailwater.

The effect of reducing the cutoff time has already been demonstrated in Section 8.2.1. The application efficiency can be improved from 67 % (Run 3) to 91 % (Run 8) by reducing the cutoff time from 150 to 100 min (see Table 8.7). The cutoff time to be adopted depends on how much under-irrigation the designer allows to occur in his design.

The second way to increase efficiency is to cut back the inflow. Runs 1 to 4 of Table 8.10 show the influence of the cutback ratio (CBR) on the application efficiency for the same data as used in Section 8.2.1. These runs were all made in Mode 3, ie, without any under-irrigation. We see that when the cutback ratio decreases from 0.9 to 0.65, the application efficiency increases from 66 % without cutback (Run 2 of Table 8.7) to 70 % for CBR = 0.8 and to 73 % for

Table 8.10 Effect of cutback ratio on application efficiency (file CUTBACK)

Run number	1	2	3	4	5	6	7
Calculation mode	3	3	3	3	4	4	4
<b>INPUT PARAMETERS</b>							
Flow rate	40	40	40	40	40	40	40
Border length	150	150	150	150	150	150	150
Border width	20	20	20	20	20	20	20
Cutoff time	—	—	—	—	120	120	120
Cutback ratio	0.9	0.8	0.7	0.65	0.9	0.8	0.7
<b>OUTPUT PARAMETERS</b>							
Cutback flow	36	32	28	26	36	32	28
Cutoff time	152	153	155	157	—	—	—
Cutback time	98	98	98	98	98	98	98
Application efficiency	68	70	73	73	82	84	85
Storage efficiency	100	100	100	100	97	97	96
Uniformity coefficient	91	91	91	91	89	88	88
Distribution uniformity	78	78	77	77	72	71	69
Deep percolation ratio	20	21	22	23	9	10	9
Surface runoff ratio	12	9	6	4	9	7	6
Minimum infiltrated depth	80	80	80	80	62	61	59
Maximum infiltrated depth	113	114	115	116	98	98	98
Average infiltrated depth	102	103	103	104	86	86	85
Over-irrigation depth	22	23	23	24	13	13	12
Under-irrigation depth	0	0	0	0	8	8	10
Over-irrigation length	150	150	150	150	100	100	100
Under-irrigation length	0	0	0	0	50	50	50
Advance time	98	98	98	98	98	98	98
Recession time	211	211	211	211	176	175	171

CBR = 0.65 (Runs 2 and 4 in Table 8.10). Values of SRR and DPR show that these improvements are due to a reduction in the surface runoff and that there is a slight increase in deep percolation. If CBR = 0.65, SRR decreases to a mere 4 %.

Runs 5 to 7 of Table 8.10 show what happens when Run 6 of Table 8.7 is adopted, ie, the cutoff time is fixed at 120 min (Mode 4). The efficiencies are much higher still, mainly because there is less percolation. Note, no result was obtained for CBR = 0.65 because not enough flow reaches the end of the border. The third way to increase the efficiency is to recover the tailwater and reuse it. If a tailwater recovery ratio (TRR) of 0.2 is used to Run 2 (Mode 3) of Table 8.7, then the application efficiency increases from 66 to 69 %. The explanation for the increase is simple. If no tailwater is recovered, then the total losses are 34 % (16 % runoff + 18 % percolation) and the application efficiency is 66 %. If, however, 20 % of the tailwater (TRR = 0.2) is reused, then there is a gain in efficiency of  $0.20 \times 16 = 3$  %, meaning that the application efficiency increases from 66 to 69 %. By the same token, if TRR = 0.8, then the application efficiency increases to 79 %.

### 8.2.5 Evaluation of field slope on system performance

So far, we have not yet addressed the issue of a particular slope of a border. To analyse the effect of the border slope on the irrigation performance, simulations for the full range of slopes were made, from minimum to maximum, as accepted by the BORDEV program. Table 8.11 shows the results for the same data as used in Section 8.2.2 (Run 2 in Table 8.8). This table shows that an increase in slope results in a decrease in advance times and an increase in the surface runoff ratios. The increase in the latter is counterbalanced by a decrease in the deep percolation ratios: the sum of both is almost constant. This is the reason that the overall application efficiencies hardly change in value. The difference between recession time and advance time ( $T_r - T_a$ ) is the same, which makes sense because the flow has to infiltrate to the same depth at the end of the field. The decrease in deep percolation ratios is thus mainly due to more uniform infiltration profiles.

Table 8.11 Influence of border slope (file SLOPE)

S	E <sub>a</sub> (%)	T <sub>a</sub> (min)	T <sub>co</sub> (min)	T <sub>r</sub> (min)	T <sub>r</sub> -T <sub>a</sub> (min)	SRR (%)	DPR (%)
0.0005	66	207	231	389	182	14	19
0.001	66	180	233	362	182	17	17
0.005	65	133	235	316	183	21	14
0.01	65	119	236	301	182	22	13
0.05	65	94	236	276	182	24	12

## 8.3 Furrow irrigation

As in basin and border irrigation, design issues in furrow irrigation also generally have to do with finding an optimum combination of design variables, notably, furrow length, flow rate and cutoff time. Other variables that are specific to furrow irrigation and, therefore, do not appear in basin irrigation, are the slope of the furrows, their spacing and their shape. As already mentioned in Chapter 3 restrictions may apply to one or more of these variables. The purpose of the design and the nature of the restrictions determine how one can use FURDEV to find an adequate solution to a furrow irrigation problem.

In Sections 8.3.1 and 8.3.2, we shall consider two examples of a furrow irrigation situation. First we will deal with how to find the best flow rate for given and fixed furrow dimensions and, second, how to find an adequate furrow length for a given flow rate. Because the nature of furrow irrigation differs in some essential respects from that of basin and border irrigation, we have varied the setup of the furrow irrigation examples accordingly. Section 8.3.3 discusses some of the operational aspects to improve the efficiency in a given situation, including how to apply cutback and reuse procedures. Finally, Section 8.3.4 is about furrow spacing a typical aspect of furrow irrigation as compared to border irrigation.

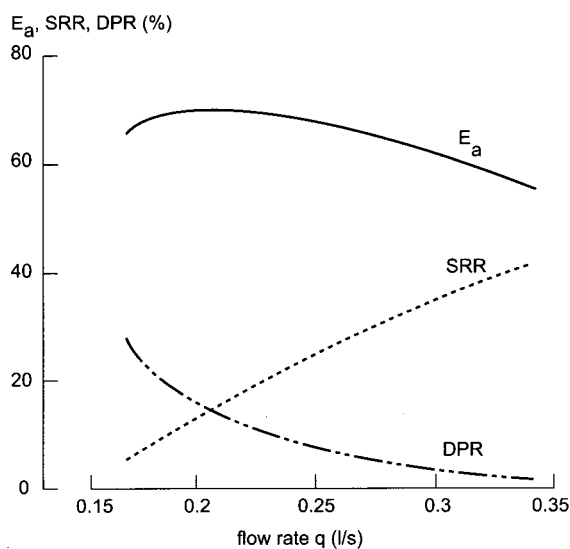
### 8.3.1 Flow rate

A design is to be made for an existing field with 100 m long furrows. The soil type is fine silty-loam and can be classified by the soil intake family # 0.5. The net irrigation requirement is 80 mm. The furrows have a triangular side slope of 1.5:1, a slope of 0.005 and a spacing of 100 cm.

To judge the best flow rate, use the application efficiency. Select Mode 1 (*Flow rate*) from the *Calculation* menu immediately after starting FURDEV to get a first approximation of the flow rate. Remember that the default operation system is fixed flow. The results are  $q = 0.28$  l/s with an  $E_a$  of 64 %. The surface runoff ratio SRR is 31 % and the deep percolation ratio DPR is 5 % (together this is 36 %, so  $E_a = 100 - 36 = 64$  %). To see how the flow rate influences the application efficiency, continue with Mode 3 (*Cutoff time*) of the *Calculation* menu. Make consecutive runs with varying  $Q$ -values, ie, 0.28, 0.26, 0.24, 0.22, 0.20, and 0.21 l/s. Table 8.12 shows that the maximum application efficiency is obtained with  $q = 0.21$  l/s, whereby the surface runoff ratio almost equals the deep percolation (with  $q = 0.22$ ,  $SRR > DPR$ ; and with  $q = 0.20$ ,  $DPR > SRR$ ). Remember that the sum of  $E_a$ , SRR, and DPR is always 100 %. Therefore,  $E_a$  is highest when  $SRR + DPR$  is lowest. This phenomenon is illustrated in Figure 8.6. Note, this result differs from that of the example in Section 8.1 for level basins. Contrary to basins, there is an optimum flow rate for furrows, one at which the application efficiency is at its highest.

Table 8.12 Determination of optimum flow rate for furrows (file FIG86)

Run number	1	2	3	4	5	6	7
Calculation mode	1	3	3	3	3	3	3
<b>INPUT PARAMETERS</b>							
Flow rate	—	0.28	0.26	0.24	0.22	0.20	0.21
Furrow length	100	100	100	100	100	100	100
<b>OUTPUT PARAMETERS</b>							
Flow rate	0.28	—	—	—	—	—	—
Cutoff time	750	750	774	810	863	945	899
Application efficiency	64	64	66	69	70	71	71
Uniformity coefficient	97	97	97	96	95	93	94
Distribution uniformity	92	92	91	88	85	81	83
Minimum infiltrated depth	80	80	80	80	80	80	80
Maximum infiltrated depth	89	89	91	95	99	106	102
Average infiltrated depth	87	87	88	90	94	99	96
Deep percolation ratio	5	5	7	9	12	17	14
Surface runoff ratio	31	31	27	23	18	13	15

Figure 8.6 Relation of flow rate  $q$  to application efficiency  $E_a$ , surface runoff ratio SRR and deep percolation ratio DPR for a furrow length  $L = 100$ 

At this flow rate, the surface runoff ratio and deep percolation ratio are equal. This is the best result possible provided the minimum infiltrated depth at the downstream end of the furrow is equal to the required depth. Note, the results



of Mode 1 with which we started this design procedure ( $q = 0.28$  l/s) did not give the optimum flow rate.

The next step is to ensure that the cutoff time will have a practical value. Suppose that in this case the designer also allows some under-irrigation. Select Mode 4 (*Minimum infiltrated depth*) and make consecutive runs with decreasing  $T_{c0}$  values till the cutoff time approximately equals the advance time. Runs 2 to 5 of Table 8.13 show that the application efficiency steadily increases from 71 to 89 %, whereas the storage efficiency and distribution uniformity steadily decrease owing to increasing under-irrigation. In Figure 8.2 you have seen a similar tendency. Here, the application efficiency is clearly no longer a yardstick to judge the irrigation performance. Instead, it is up to the designer to choose how much under-irrigation he allows to occur in his design. Certain threshold values of the storage efficiency and distribution uniformity unfortunately cannot be used for this purpose because they will have different

Table 8.13 Results of the trial runs for different cutoff times (file DESIGN1)

Run number	1	2	3	4	5
Calculation mode	4	4	4	4	4
INPUT PARAMETERS					
Flow rate	0.21	0.21	0.21	0.21	0.21
Furrow length	100	100	100	100	100
Cutoff time	900	840	780	720	660
Required depth	80	80	80	80	80
Flow resistance	0.04	0.04	0.04	0.04	0.04
Furrow slope	0.005	0.005	0.005	0.005	0.005
Furrow spacing	1	1	1	1	1
Side slope	1.5	1.5	1.5	1.5	1.5
SCS #	0.5	0.5	0.5	0.5	0.5
OUTPUT PARAMETERS					
Application efficiency	71	76	80	85	89
Storage efficiency	100	100	99	97	93
Uniformity coefficient	94	94	93	92	92
Distribution uniformity	83	82	81	79	77
Deep percolation ratio	14	11	7	3	0
Surface runoff ratio	15	14	13	12	10
Minimum infiltrated depth	80	75	69	63	57
Maximum infiltrated depth	102	97	92	87	81
Average infiltrated depth	96	91	86	80	75
Over-irrigation depth	16	13	9	5	1
Under-irrigation depth	0	2	5	7	8
Over-irrigation length	100	87	75	58	29
Under-irrigation length	0	13	25	42	71
Advance time	276	276	276	276	276
Recession time	928	868	808	747	687

values for different combinations of input parameters. Therefore, we propose using a certain percentage of the required depth, for instance 10 %, to be allowed as average under-irrigation depth. If this percentage is adopted Table 8.13 shows that you will get a cutoff time of 660 min that is acceptable for the final design.

### 8.3.2 Furrow length

A design is to be made for a situation where the available flow rate is fixed at 1.0 l/s. The soil type is silty-loam and can be classified by the soil intake family # 0.6. The net irrigation requirement is 100 mm. The furrows have a triangular side slope of 1:1, a slope of 0.008, and a spacing of 75 cm.

To judge the best furrow length, use again the application efficiency. Select Mode 2 (*Dimensions*) from the Calculation menu immediately after starting FURDEV, to get a first approximation of the furrow length. The results are  $L = 338$  m, with an  $E_a$  of 71 %. The SRR is 14 % and the DPR is 16 %, which are virtually equal indicating almost optimum conditions.

The next step is to ensure that the furrow length will have a value that is practical. Suppose that a furrow length of 338 m is not feasible in the overall layout. Run FURDEV in Mode 3 for different furrow lengths to see how this influences the application efficiency. The results in Figure 8.7 shows no significant change in the application efficiency whether the furrow length adopted in the final design is 300 m or whether it is 350 m. Suppose a furrow length of 350 is selected. You will see in Figure 8.7 that the optimum application efficiency is obtained where the surface runoff ratio equals the deep percolation ratio.

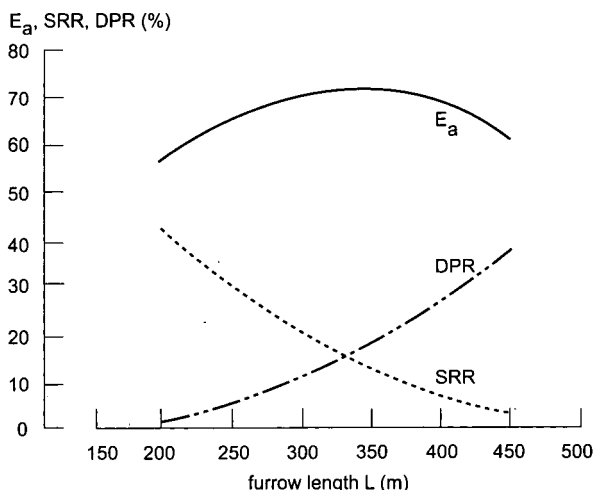


Figure 8.7 Relation of furrow length  $L$  to application efficiency  $E_a$ , surface runoff ratio SRR and deep percolation ratio DPR

The following step is to ensure that the cutoff time will have a practical value. Running FURDEV in Mode 3 will generally give odd values for the resulting cutoff time. Select Mode 4 (*Minimum infiltrated depth*) and change the cutoff time from 620 to 600 min (= 10 hours). The minimum infiltrated depth slightly decreases from 100 to 97 mm and the application efficiency slightly increases from 71 to 73 % (Run 3 in Table 8.14). This is still an acceptable design.

The last step is to make sensitivity analyses on the field parameters used in the design, ie, intake family, flow resistance and furrow shape. Runs 4 to 6 in Table 8.14 show that the variation in infiltration and flow resistance properties results in significantly different amounts of over-irrigation and corre-

Table 8.14 Results of design furrow length and sensitivity (file DESIGN2)

Run number	1	2	3	4	5	6	7
Calculation mode	2	3	4	4	4	4	4
<b>INPUT PARAMETERS</b>							
Flow rate	1	1	1	1	1	1	1
Furrow length	—	350	350	350	350	350	350
Cutoff time	—	—	600	600	600	600	600
Required depth	100	100	100	100	100	100	100
Flow resistance	0.04	0.04	0.04	0.04	0.04	0.08	0.04
Furrow slope	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Furrow spacing	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Side slope	1	1	1	1	1	1	2
Bed width	—	—	—	—	—	—	—
SCS #	0.6	0.6	0.6	0.6	0.7	0.6	0.6
<b>OUTPUT PARAMETERS</b>							
Furrow length	338	—	—	—	—	—	—
Cutoff time	596	620	—	—	—	—	—
Application efficiency	71	71	73	73	72	72	73
Storage efficiency	100	100	100	99	99	99	100
Uniformity coefficient	93	93	93	96	87	86	92
Distribution uniformity	82	80	79	88	63	61	79
Deep percolation ratio	16	18	16	5	24	25	15
Surface runoff ratio	14	12	11	22	3	3	12
Minimum infiltrated depth	100	100	97	95	83	81	96
Maximum infiltrated depth	131	134	131	112	150	152	131
Average infiltrated depth	122	125	122	107	133	133	121
Over-irrigation depth	22	25	23	9	38	39	23
Under-irrigation depth	0	0	2	2	6	8	1
Over-irrigation length	338	350	335	292	306	306	321
Under-irrigation length	0	0	15	58	44	44	29
Advance time	226	251	251	177	372	417	256
Recession time	647	672	652	658	645	672	655

sponding deep percolation ratios. The variations in the latter are counterbalanced by the surface runoff ratios: the sum of both is almost constant. This is the reason that the overall application efficiencies hardly change in value. The amount of under-irrigation slightly increases in Runs 5 and 6, but only over a relatively short length. Run 7 in Table 8.14 shows that the effect of a different furrow shape is almost negligible on the irrigation performance. The conclusion is that this design is not very sensitive to changes in the assumed field parameters. This picture may change, of course, if other combinations of input variables would be used.

The two previous examples only showed certain elements of the design procedure. There are no general and strict guidelines for all design situations. Each specific combination of parameters will have its own solution, which will depend on the prevailing objectives, practices, and so on. Nevertheless, the following guidelines can be formulated on how to use FURDEV in the design process:

- Run FURDEV in Modes 1 or 2 to get a first value on the flow rate or the border dimensions. If you have sufficient experience, start immediately in Mode 3.
- Proceed to Mode 3 and vary the flow rates or furrow lengths to see how the application efficiency will vary accordingly. The maximum application efficiency is obtained when the surface runoff ratio equals the deep percolation ratio. Select a flow rate and/or furrow length that are feasible. This gives the best design possible provided the minimum infiltrated depth at the downstream end of the furrow is equal to the required depth.
- Proceed to Mode 4 to make refinements to the cutoff time. If you do not allow under-irrigation to occur in your design, the cutoff time as obtained from Mode 3 only needs to be rounded off to the nearest practical value.
- If you allow under-irrigation in your design, reduce the cutoff time in a stepwise manner till it approximately equals the advance time. Determine the minimum cutoff time, using a certain percentage of the required depth to be allowed as average under-irrigation depth as a yardstick.
- Finally, do sensitivity analyses of the field parameters (also in Mode 4) to see if it is possible to retain the selected design.

### **8.3.3 Operational aspects**

In the previous examples, it has been shown how to arrive at an optimum design combination of furrow length and flow rate for given field parameters. In most cases, it will be possible to obtain an irrigation efficiency of about 70 %. Although this is reasonable, one may wish to improve on it. There are three ways of doing this: reducing the cutoff time and accepting some under-irrigation at the far end of the field, applying cutback on the inflow, or reusing the tailwater.

The effect of reducing the cutoff time was already illustrated in Section 8.3.1. The application efficiency can be improved from 71 % (Run 1) to 89 % (Run 5) by reducing the cutoff time from 900 to 660 min (see Table 8.13). The cutoff time to be adopted depends on how much under-irrigation the designer allows to occur in his design.

The second way to increase efficiency is to cut back the inflow. Runs 1 to 4 of Table 8.15 shows the influence of the cutback ratio (CBR) on the application efficiency for the same data as used in Section 8.3.1. These runs were all made in Mode 3, ie, without any under-irrigation. We see that when the cutback ratio decreases from 0.9 to 0.65, the application efficiency increases from 71 % without cutback (Run 1 of Table 8.13) to 80 % for CBR = 0.8 and to 91 % for CBR = 0.65 (Runs 2 and 4 in Table 8.15). Values of SRR and DPR show that these improvements are due to a reduction in the surface runoff and deep percolation ratios. Initially, the deep percolation ratio slightly increases (Run 2), but decreases in Runs 3 and 4 because there is no surface runoff any longer. Run 5 of Table 8.15 shows what happens when Run 5 of Table 8.13 is adopted, ie,

Table 8.15 Effect of cutback ratio on application efficiency (file CUTBACK)

Run number	1	2	3	4	5
Calculation mode	3	3	3	3	4
<b>INPUT PARAMETERS</b>					
Flow rate	0.21	0.21	0.21	0.21	0.21
Furrow length	100	100	100	100	100
Cutoff time	—	—	—	—	660
Cutback ratio	0.9	0.8	0.7	0.65	0.9
<b>OUTPUT PARAMETERS</b>					
Cutback flow	0.19	0.17	0.15	0.14	0.19
Cutoff time	901	902	904	905	—
Application efficiency	74	80	87	91	95
Storage efficiency	100	100	100	100	93
Uniformity coefficient	94	94	94	94	92
Distribution uniformity	83	83	83	83	77
Deep percolation ratio	15	16	13	9	0
Surface runoff ratio	11	4	0	0	5
Minimum infiltrated depth	80	80	80	80	57
Maximum infiltrated depth	102	102	103	103	81
Average infiltrated depth	96	96	96	96	75
Over-irrigation depth	16	16	16	16	1
Under-irrigation depth	0	0	0	0	8
Over-irrigation length	100	100	100	100	29
Under-irrigation length	0	0	0	0	71
Advance time	276	276	276	276	276
Recession time	928	928	928	928	686

the cutoff time is fixed at 660 min (Mode 4). The efficiency is much higher still, mainly because there is no percolation. Note, no results were obtained for CBR < 0.9 because not enough flow reaches the end of the furrow.

The third way to increase the efficiency is to recover the tailwater and reuse it. If a tailwater recovery ratio (TRR) of 0.2 is used to Run 1 (Mode 3) of Table 8.13, then the application efficiency increases from 71 to 74 %. The explanation for the increase is simple. If no tailwater is recovered, then the total losses are 29 % (15 % runoff + 14 % percolation) and the application efficiency is 71 %. If, however, 20 % of the tailwater (TRR = 0.2) is reused, then there is a gain in efficiency of  $0.20 \times 15 = 3$  %, meaning that the application efficiency increases from 71 to 74 %. By the same token, if TRR = 0.8, then the application efficiency increases to 83 %.

### 8.3.4 Evaluation of furrow spacing on system performance

So far, we have not yet addressed the issue of the furrow spacing. To analyse the effect of the furrow spacing on irrigation performance, simulations for the full range of spacings were made, from minimum to maximum, as accepted by the FURDEV program. Table 8.16 shows the results for the same data as used in Section 8.3.2 (Run 2 in Table 8.8). This table shows that an increase in furrow spacing results in an initial decrease in advance time and an increase in the surface runoff ratio. The increase in the latter is more or less counterbalanced by a decrease in the deep percolation ratios: the sum of both is almost constant. This is the reason that the overall application efficiencies hardly change in value, except for very narrow furrow spacings. These phenomena need to be explained in more detail.

The decrease in advance time is because the infiltration parameters  $k$  and  $f_0$  are corrected in FURDEV by the ratio of wetted perimeter and furrow spacing. An increase in furrow spacing thus results in a lower infiltration rate and

Table 8.16 Influence of border slope (file SLOPE)

Spacing (m)	$E_a$ (%)	$T_a$ (min)	$T_{co}$ (min)	$T_r$ (min)	$T_r - T_a$ (min)	SRR (%)	DPR (%)
0.6	50	506	693	734	225	1	48
0.7	67	306	606	654	348	7	25
0.8	71	211	658	713	502	17	12
0.9	70	192	753	811	619	22	8
1.0	69	192	845	904	712	24	7
1.1	68	192	939	999	807	25	6
1.2	68	192	1035	1096	904	27	6
1.3	67	192	1133	1194	1002	28	5
1.4	66	192	1233	1294	1102	29	5
1.5	66	192	1334	1396	1204	30	4

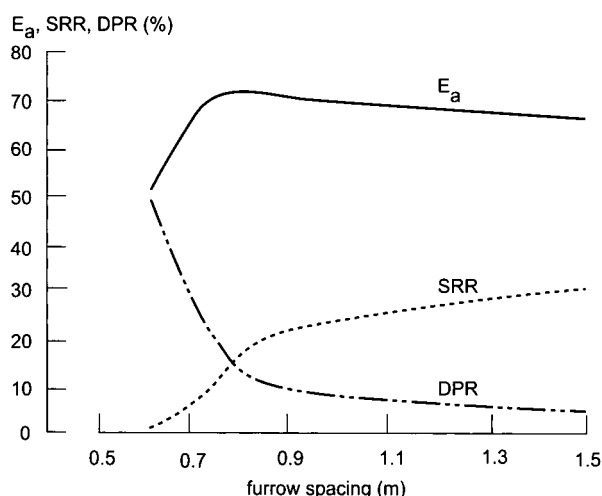


Figure 8.8 Relation of furrow spacing to application efficiency  $E_a$ , surface runoff ratio SRR and deep percolation ratio DPR

consequently in a shorter advance time. If this reduction factor drops below 0.5, FURDEV assumes a constant value of 0.5.

The increase in opportunity time ( $T_r - T_a$ ) is initially the combined effect of a lower infiltration velocity and a larger volume of water required to infiltrate to the proper depth over each metre of length because a wider furrow spacing means that the water has to infiltrate over a broader area. Once the reduction factor drops below 0.5 and becomes a constant, the increase in opportunity time is only because a larger volume of water is required to infiltrate to the proper depth.

The combined effect of an initial decrease in advance time and an increase in opportunity time results in an overall increase in cutoff time. This explains the increase in the surface runoff ratio. The decrease in the deep percolation ratio is mainly due to more uniform infiltration profiles, ie, shorter advance times.

Finally, it can be noted that the rates of increase and decrease for the various parameters are different. This results, among other things, in local minimum values of the cutoff and recession times. The relative changes in application efficiency, surface runoff ratio, and deep percolation ratio are illustrated in Figure 8.8. It shows that the optimum application efficiency is again obtained when the surface runoff ratio equals the deep percolation ratio. It also shows that the effect of furrow spacing on the system performance is almost negligible in the range of 0.75 to 1.0 m.





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# Appendix A:

## The BASDEV calculation model

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## List of symbols Appendix A

A	Cross-sectional area
A	Infiltration exponent
ALR	Advance length ratio
b	Subscript that denotes the beginning of a time step
d	Flow depth
$d_i$	Water depth at section inflow
$d_{ie}$	Water depth at section inflow at the end of time step
$d_r$	Water depth at section inflow
$d_{rb}$	Water depth at section inflow at the beginning of a time step
$d_{re}$	Water depth at section inflow at the end of a time step
D	Infiltrated depth
$D_{av}$	Average infiltrated depth
$D_i$	Infiltrated depth
$D_{ip}$	Infiltrated depth from the completion of advance till cutoff time
$D_{ir}$	Difference between required depth and infiltrated depth $D_{ip}$
$D_{le}$	Infiltrated depth at the left end of a section at the end of a time step
$D_{min}$	Minimum infiltrated depth
$D_{re}$	Infiltrated depth at the right end of a section at the end of a time step
$D_{req}$	Required infiltration depth
$D_s$	Stored water depth
$D_{sp}$	Depth of water stored at the end of the ponding phase
e	Subscript that denotes the end of a time step
$E_a$	Application efficiency
Fac	Factor used to arrive at a suitable basin length or flow rate
j	Subscript that denotes a section
k	Subscript that denotes a time step
k	Infiltration coefficient
l	Subscript denoting the left-hand side of a section
L	Section length
L	Basin length
$L_1$	First estimate of a suitable basin length
$L_2$	Second estimate of a suitable basin length
n	Manning's roughness coefficient
q	Flow rate per metre width
$q_i$	Section inflow
$q_{ib}$	Section inflow at the beginning of a time step
$q_{ie}$	Section inflow at the end of a time step
$q_r$	Section outflow
$q_{rb}$	Section outflow at the beginning of a time step
$q_{re}$	Section outflow at the end of a time step

$Q$	Flow rate
$Q_1$	First estimate of a suitable flow rate
$Q_2$	Second estimate of a suitable flow rate
$r$	Subscript denoting the right-hand side of a section
$r_y$	Surface shape factor
$r_z$	Infiltration shape factor
$R$	Hydraulic radius
$S$	Hydraulic gradient
$t$	Time
$t_b$	Time at the beginning of infiltration
$t_e$	Time at the end of infiltration
$t_{lb}$	Time at the beginning of infiltration on the left side of a section
$t_{le}$	Time at the end of infiltration on the left side of a section
$t_{rb}$	Time at the beginning of infiltration on the right side of a section
$t_{re}$	Time at the end of infiltration on the right side of a section
$t_p$	Time at the end of the ponding phase
$T_a$	Advance time
$T_{co}$	Cutoff time
$T_i$	Infiltration opportunity time
$T_{req}$	Time needed to infiltrate the required depth
$V_{ni}$	Net volume of inflow over a time step
$VI$	Infiltrated volume
$VI_b$	Infiltrated volume at the beginning of a time step
$VI_e$	Infiltrated volume at the end of a time step
$VS$	Volume of surface storage
$VS_a$	Surface storage at the end of the advance phase
$VS_b$	Surface storage at the beginning of a time step
$VS_e$	Surface storage at the end of a time step
$VS_p$	Increase in surface storage from the completion of advance till cutoff time
$W$	Basin width
$\alpha$	Empirical shape factor for the tip cell
$\Delta$	Standard section length of a basin

## A1 General approach

The advance phase of basin irrigation is the part of the BASDEV calculation model that is the most crucial and most extensive. Most of this Appendix is devoted to this phase. To simulate the advance phase BASDEV divides a basin into sections of equal length, distinguishing different types of cells in each section. We discuss these cells in detail in Section A2.1.

BASDEV establishes two equations for each basin section and each type of cell: a flow equation that describes the surface flow of irrigation water; and a volume balance equation in which the difference between inflow and outflow of the cell equals the sum of changes in infiltration and surface storage. BASDEV uses these equations to calculate the time step (ie, the time it takes the flow of irrigation water to move through the basin section). We discuss the equations in Sections A2.2 and A2.3, and in Section A2.4 we discuss how to solve the equations.

BASDEV works with the unit flow concept, which means that it divides the total basin inflow,  $Q$ , by the basin width and uses the resulting *unit flow rate*,  $q$ , in the simulation. Thus, BASDEV assumes a two-dimensional process that involves two directions, namely, lengthwise (ie, the direction of flow along the surface of the basin) and vertical (ie, the direction of flow infiltration into the soil).

For the calculations that deal with the periods after advance and cutoff, the different sections are no longer necessary, and so BASDEV treats the basin as one reach. In addition, BASDEV no longer calculates time steps, instead, it establishes volume balances for the entire basin length for the moments of advance time and cutoff time (Section A3). An important aspect of the calculation procedure is that the calculations are valid only for situations in which inflow is cut off after surface flow has reached the end of the basin.

Section A4 discusses the calculation procedures for the four calculation modes. Section A5 explains model verification and Section A6 outlines the various assumptions that are included in the model schematisation.

In this Appendix we use the two subscripts below:

1.  $j$ , which stands for a particular section (eg, 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> section, up to the  $n^{\text{th}}$  section). We can be even more precise by specifying either  $jl$  for the left-hand (downstream) side of the section or  $jr$  for the right-hand (upstream) side.
2.  $k$ , which stands for a particular time step (eg, 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> time step, up to the  $n^{\text{th}}$  time step) from the beginning of an irrigation turn. We can be even more precise by specifying either  $kb$  for the beginning of the time step or  $ke$  for the end of the time step.

So, for example, the subscripts  $4l;5e$  stand for the left side of the fourth section at the end of the fifth time step. Note that when there is  $jr$  and  $ke$ , this is the same as  $j+1,l;k+1,b$  or, expressed differently, it is true that  $jr; ke = j + 1,l; k + 1,b$ .

## A2 Modelling the advance phase

### A2.1 Sections and cells

BASDEV divides the basin length into 10 equal sections and, for each section, calculates the time taken for surface flow to move from the upstream end to the downstream end. Thus, the number of time steps is equal to the number of sections. But, whereas all of the sections are of equal length, the duration of the time steps varies, increasing in the downstream direction. In this respect BASDEV's approach differs from the usual method of hydrodynamic modelling, which first assumes equal time steps and then calculates the corresponding (varying) section lengths (see, for example, Strelkoff and Katopodes 1977, or Katopodes and Strelkoff 1977).

BASDEV makes a distinction between the inlet section and all the other sections, because inflow into the inlet section is both known and constant, while inflow into all the other sections needs to be calculated separately. There are three types of cells in the inlet section and all the other sections with the exception of the last two sections, namely, *tip cells*, *rising cells* and *normal cells* (Figure A.1). The *tip cell* represents the advance front during the first time step: water enters a section and advances to the end of it. During the next time step the tip cell becomes a *rising cell* or *Eulerian penultimate cell* (Walker and Skogerboe 1987). The characteristics of the rising cell are a lack of surface water depth and a lack of infiltrated depth at the downstream end of the section at the beginning of the time step. During the remaining time steps the rising cell changes into a *normal cell*, which is characterised by

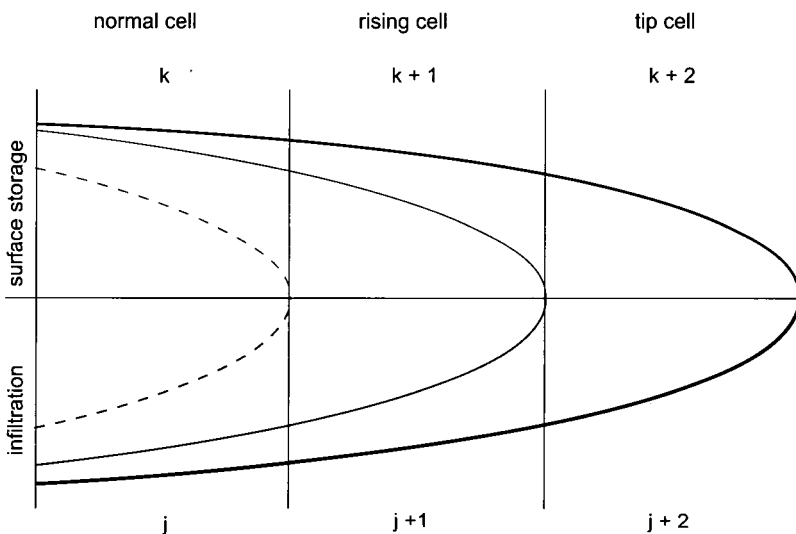


Figure A.1 The three types of cells in a section

increasing upstream and downstream surface depths and infiltration depths. In the last section, only a tip cell is present, while in the penultimate section, only a tip cell and a rising cell are present. In the two-before-last section a tip cell, a rising cell and a normal cell are present. One normal cell is added in each previous section, so that the inlet section has a tip cell, a rising cell and eight normal cells.

There are two equations for each cell: a flow equation (for energy conservation) and a volume balance equation (for mass conservation). Thus, the advance of the irrigation front over the 10 sections of the basin can be described by  $(10 \text{ tip cells} + 9 \text{ rising cells} + 36 \text{ normal cells}) \times 2 \text{ equations} = 110 \text{ equations}$ . We shall describe the procedure for solving these equations in Section A2.4, but before doing so, we shall provide some more information about the equations. Fortunately, the total set of 110 equations contains only 12 different types of equations (two equations each for the three types of cells multiplied by the two types of sections (inlet and others)). Figure A.2 illustrates the equation sequence. The figure also illustrates the progress of flow (j,k), with j = section number and k = time step counted from  $T = 0$ . As mentioned above, (2,3) means: second section, third time step. Note, only the first three cell situations are different in the inlet section. From the inlet section

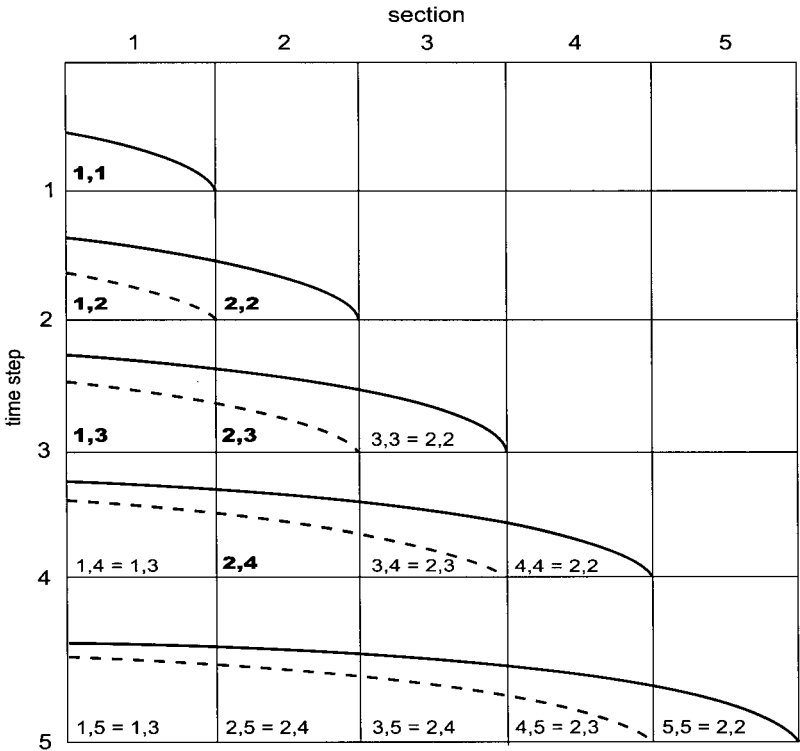


Figure A.2 Sequence of the equations used

onwards, barring the last two sections, there are only normal cells, and the equations used in (1,4), (1,5), and so on are the same as those used in (1,3). In one particular cell  $j$  the tip cell occurs during a particular time step  $k$ ; the rising cell occurs during  $(j,k+1)$ ; and first normal cell occurs during  $(j,k+2)$ . From  $j,k+2$  onwards, the equations are the same. Thus, the equations that we shall consider below are valid in the following situations (section and time)

	Inlet section ( $j = 1$ )	All other sections except for the last two sections ( $j \geq 2$ )
Tip cell	$k = 1$	$k = j$
Rising cell	$k = 2$	$k = j + 1$
Normal cell	$k \geq 3$	$k \geq j + 2$

In the discussion that follows, we shall consider only the basic equations, dividing them into flow equations and volume balance equations. The equations for the inlet cell are a special case and are not the same as the general equations for the other cells.

## A2.2 Basic flow equations

BASDEV uses Manning's equation to compute the surface flow, applying different assumptions according to the different cells. The general equation reads

$$Q = \frac{1}{n} AR^{2/3} S^{1/3} \quad (\text{A.1})$$

where

$Q$  = flow rate

$n$  = Manning's flow resistance coefficient

$A$  = wet cross section

$R$  = hydraulic radius of the flow cross-section

$S$  = hydraulic gradient

With water depth,  $d$ , the unit flow rate per metre width,  $q$ , becomes

$$q = \frac{1}{n} d^{5/3} S^{1/2} \quad (\text{A.2})$$



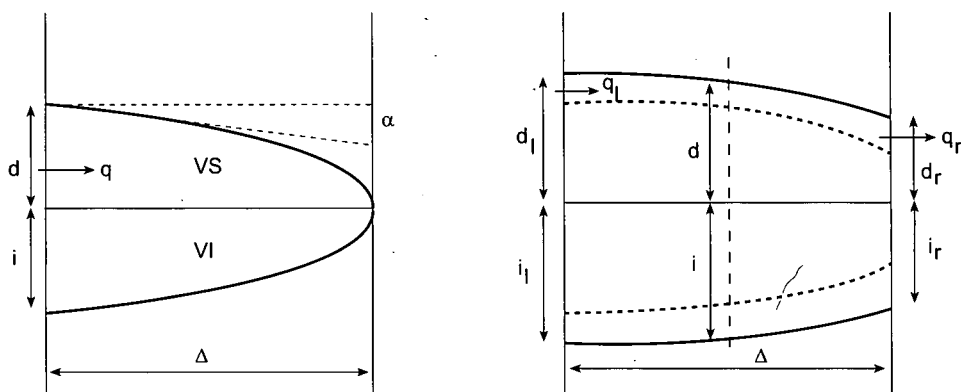


Figure A.3 Principles of the flow equations

Further detailing of  $q$ ,  $d$ , and  $S$  depends on the section and the cell type. BASDEV establishes all flow equations for the end of the time step.

For a tip cell (Figure A.3, left-hand side) with a bed slope of zero and a surface flow profile not yet fully developed, BASDEV assumed the following for the hydraulic gradient

$$S = \alpha \frac{d}{\Delta} \quad (\text{A.3})$$

where  $\Delta$  is the standard section length,  $\Delta = L/10$ . Modelling trials (ie, dividing a tip cell into 10 sections, doing many runs with the program for different combinations of input using different values for  $\alpha$ , and determining the upstream profile tangent for the entire tip cell) yielded a value of  $\alpha = 0.4$ , independent of the input. There is no outflow for a tip cell, so  $q$  is the inflow that occurs on the left-hand side of the cell, taken at the end of the time step. Combining Equations A.2 and A.3 for a tip cell yields:

$$q_{le} = \frac{1}{n} \left( \frac{0.4}{\Delta} \right)^{1/2} d_{le}^{13/6} \quad (\text{A.4})$$

or, for 10 sections:  $q_{le} = (2 / n \sqrt{L}) d_{le}^{13/6}$

In contrast to the tip cell, where inflow occurs on the left-hand side only, normal cells and rising cells have different flows on both sides, ie, the right-hand and the left-hand sides. The flow equation is now established for the middle of the section. This means that in Equation A.2, the flow  $q$  is defined as the average of inflow and outflow  $q = \frac{1}{2} (q_l + q_r)$ . In the same equation, the depth

$d$  is defined as the average depth  $d = \frac{1}{2} (d_l + d_r)$ . And the gradient  $S$  is defined as  $S = (d_l - d_r)/\Delta$ . Again, all of these values are taken at the end of the time step (Figure A.3, right-hand side).

The value  $q_{le}$  is the section inflow,  $q_{re}$  is the section outflow,  $d_{le}$  the inflow depth and  $d_{re}$  the outflow depth. Thus, the assumption is that there is a linear decrease of flow and a linear surface profile over the section length, and that the flow equation for the normal cell of section  $j$  now reads

$$\frac{q_{le} + q_{re}}{2} = \frac{1}{n} \left( \frac{d_{le} + d_{re}}{2} \right)^{5/3} \left( \frac{d_{le} + d_{re}}{2\Delta} \right)^{1/2} \quad (A.5)$$

The same equation is valid for the rising cell, because  $d_{rb}$  (being equal to zero) is not present. For the specific equations for the inlet cell, the above equations are used with  $q$  (being equal to  $\frac{1}{2} (q + q)$ ) on the left-hand side.

### A2.3 Basic volume balance equations

#### *General volume balance equation*

The general volume balance equation for one section and one time step reads

$$V_{ni} = VS_e + VI_e - VS_b - VI_b \quad (A.6)$$

where

$V_{ni}$  = net inflow volume over a time step

$VS$  = surface volume

$VI$  = infiltrated volume

$b, e$  = subscripts indicating the beginning (b) and the end (e) of the time step

We developed the equations below for  $V_{ni}$  (expressed in flow rates,  $q$ ) for  $VS$  and for  $VI$ . To continue, calculate the total volumes at the end of the time step  $VS_e$  and  $VI_e$  and then subtract from them the values of  $VS_b$  and  $VI_b$  from the end of the previous time step.

#### *Net inflow equations*

All net inflows are calculated as the difference between inflow and outflow in a section and averaged over a time step. Thus, the general equation for the net inflow  $V_{ni}$  over a time step  $t_b$  to  $t_e$  reads

$$V_{ni} = \left( \frac{q_{lb} + q_{le}}{2} - \frac{q_{rb} + q_{re}}{2} \right) (t_e - t_b) \quad (A.7)$$

with b and e once again indicating the beginning and end of the time step, and l and r indicating the inflow and outflow for the time step. The equation assumes a linear increase of inflow and outflow over the time step.

This general equation can be adapted for any specific cell or section by inserting the appropriate indices. For a tip cell  $q_{lb} = q_{rb} = q_{re} = 0$ , for a rising cell  $q_{rb} = 0$ , and for the inlet section  $q_{lb} = q_{le} = q$ .

### *Surface storage equations*

There is no general surface storage equation that is valid for all sections and cells. The equations for tip cells and other cells are different. To calculate the surface storage for all rising and normal cells, we use the average depth over the section. Thus the equation for non-inlet sections becomes

$$VS = \Delta \frac{d_l + d_r}{2} \quad (A.8)$$

which assumes a linear depth profile over the section. This equation is applied for the end of a time step ( $VS_e$ ) and for the end of the previous time step ( $VS_b$ ). For the tip cell, there is no water depth at the beginning of the time step, whereas at the end of the time step there is an upstream depth but still no downstream depth. The surface volume at the end of the time step could be described as

$$VS = r_y d_{le} \Delta \quad (A.9)$$

where  $d_{le}$  is the upstream (left) surface depth, always taken at the end of the time step for the  $j^{th}$  section. According to Strelkoff and Katopodes (1977), the surface shape factor  $r_y$  can be set at  $r_y = 0.7$ . The tip cell equation thus yields

$$VS = 0.7 d_{le} \Delta \quad (A.10)$$

The equations for the inlet cell can be derived from the foregoing.

### *Infiltration equations*

All infiltration is calculated using Kostikov's equation

$$D_i = k T_i^A \quad (A.11)$$

where

$D_i$  = accumulated infiltrated depth

$T_i$  = infiltration opportunity time

$k, A$  = constants

Infiltration generally does not start at  $T = 0$  (the beginning of the irrigation inflow), but some time,  $t_b$ , later. The infiltration opportunity time equals  $(t_e - t_b)$ , so that

$$D_i = k (t_e - t_b)^A \quad (\text{A.12})$$

Note, except for the tip cell of the inlet section,  $t_b$  is always different for all sections and cells and  $(t_e - t_b)$  varies with the time step concerned. No tip cell of any section has any infiltration at the beginning of the time step. There is only an infiltrated depth at the upstream end at the end of the time step. Similar to the surface storage of the tip cell (Equation A.9), the infiltrated volume over the tip cell equals

$$VI = r_z \Delta k (t_{le} - t_{lb})^A \quad (\text{A.13})$$

with  $r_z$  being a factor that takes into account the shape of the subsurface infiltration profile. We see in Strelkoff (1977) that this  $r_z$  equals  $1/(1+A)$ , consequently, the infiltrated volume of a tip cell is

$$VI = \frac{\Delta k}{1 + A} (t_{le} - t_{lb}) \quad (\text{A.14})$$

The equation for the normal cells and rising cells differs from that for the tip cell in two respects. First, at the end of a time step, there is an infiltrated depth at both the upstream and the downstream end of the section. For these infiltrated depths  $D_{le}$  and  $D_{re}$ , we assume that the infiltrated volume  $VI$  is

$$VI = \Delta \frac{D_{le} + D_{re}}{2} \quad (\text{A.15})$$

We also assume that the infiltration profile, in contrast to the tip cell, is linear. So, the second difference between the equation for the normal and rising cells and the equation for the tip cell is that the infiltration opportunity time is longer than one time step and that it varies with the section and the cell. The reason for the variation is that infiltration in the different sections starts at different moments (remember that the length of the time step for the different sections and cells also varies). If we assume that the infiltration profile is linear, then combining Equation A.12 and A.15 yields

$$VI = \Delta D_{av} = \Delta k \frac{(t_{le} - t_{lb})^A + (t_{re} - t_{rb})^A}{2} \quad (\text{A.16})$$

Note, infiltration starts one step earlier on the left side of a cell than on the right side, therefore,  $t_{le}-t_{lb}$  is not equal to  $t_{re} - t_{rb}$ .

## A2.4 Calculation procedures

When the basin is divided into  $n$  sections, the total number of equations to be calculated is  $6(n-1)$ , so there are 54 equations for  $n = 10$ . These include the equations for  $n$  distance steps and for each of the time steps. In addition, for each step, BASDEV establishes the flow equation and the volume balance equation consisting of three elements, and uses these equations for the time step  $k$  with the Newton-Raphson technique. For information on the principles of this technique see, among others, Fread and Harbaugh (1971) and Walker and Skogerboe (1987). BASDEV uses the technique to get all the values for  $q$ ,  $d$ , and  $D_i$  on both sides of a cell for the end of the previous time step, whereby new values for the end of the current time step can be calculated.

The calculations deal first with the tip cell and then with the cells farther upstream. For example, when flow enters Section 5, BASDEV calculates time step 5 for the tip cell in Section 5. After the program has done this, it calculates the rising cell in Section 4 and then the normal cells in Sections 3, 2 and 1. It performs these calculations iteratively for each cell until the error in the volume balance is less than 0.1%. At the end of each time step, when BASDEV has calculated all of the sections, it checks an extra volume balance for the entire field length that it has covered (from  $T = 0$ ), and this has to yield an error of less than 0.5%.

Finding a way to solve the sets of equations when the basin inflow is set at zero seems to be impossible. This means that, in principle, the BASDEV results are valid only as long as the cutoff time is equal to at least the advance time.

## A3 Modelling of depletion and recession

BASDEV uses a simple procedure to model the depletion and recession that occurs after surface flow has reached the end of a basin. This procedure is based on several assumptions, the first one being that at the start of advance time,  $T_a$ , there is a certain volume of water,  $VS_a$ , lying stored on the basin's surface. From this moment,  $T_a$ , until the beginning of cutoff time,  $T_{co}$  (a period known as the ponding phase), the basin receives an additional volume of water,  $VS_p$ . BASDEV assumes that, during the ponding phase, the combined volumes spread out horizontally over the basin's surface. It also assumes that, at the end of the basin, the water infiltrates to the depth that corresponds to the combined volumes. This is because at the end of advance time, infiltration at the basin end is zero. BASDEV adds the amount of this same depth to the infiltrated depths at all other points along the length of the basin. Finally,

BASDEV assumes that recession occurs at the same moment over the whole basin or, in other words, that the recession curve is horizontal. This procedure yields the values of infiltrated volumes and depths. Once we know these values, we can calculate the various infiltration parameters (eg, the average depth,  $D_{av}$ , and the stored depth,  $D_s$ , in the  $D_{req}$  zone). In addition, we can find and evaluate all the performance indicators.

The calculation procedure in Modes 1, 2 and 3 of BASDEV differs slightly from the one in Mode 4. Nevertheless, the procedure in Mode 4 is based on the same principles. Modes 1, 2 and 3 have seven main points. These are:

1. At the end of advance time,  $T_a$ , the infiltrated depth at the end of the basin is still zero. During the ponding phase, which lasts from  $T_a$  to  $T_{co}$ , the infiltrated depth becomes  $D_{ip} = k(T_{co} - T_a)^A$ .
2. The difference between the infiltrated depth,  $D_{ip}$ , and the required depth,  $D_{req}$ , is  $D_{ir} = D_{req} - D_{ip}$ .
3. We know the amount of surface volume storage,  $VS_a$ , that is present at the start of advance time,  $T_a$ , from the previous calculations.
4. The amount of additional volume,  $VS_p$ , that is supplied during the ponding phase works out to  $VS_p = Q(T_{co} - T_a)$ .
5. We assume that, during the ponding phase, the two surface volumes,  $VS_a + VS_p$ , spread themselves out over the basin to an average depth,  $D_{sp}$ , and that  $D_{sp} = (VS_a + VS_p)/(WL)$ .
6. Subsequently, we also assume that  $D_{sp} = D_{ir}$  (see Point 2 above), or  $(VS_a + VS_p)/(WL) = D_{req} - k(T_{co} - T_a)^A$ .
7. With this equation, we can solve  $T_{co} - T_a$ , which will give us the value of  $T_{co}$ .

For Mode 4 the five main points are as follows:

1. The surface depth,  $D_{sp}$ , can be calculated from the value of  $T_{co}$ , which we already know.
2. Here again, we assume that the value of  $D_{ir}$  is equal to the value of  $D_{sp}$  (see Point 6 above).
3.  $D_{ip}$  can be calculated with the known value of  $T_{co}$ .
4. It is now possible to calculate the minimum infiltrated depth,  $D_{min}$ , as  $D_{min} = D_{ir} + D_{ip}$ .
5. Because the value of  $T_{co}$  is a given,  $D_{min}$  will usually not be equal to  $D_{req}$ .

The points above (and hence the calculation procedure) are correct as long as we assume that  $T_{co} - T_a$  is sufficient time for the ponded water to spread out within the given basin dimensions before recession starts somewhere on the basin. All basin irrigation programs use this assumption. In practice, the assumption is correct if  $T_{co} \geq T_a$ . It is not correct, however, if flow is cut off long before the end of advance time. When this happens, the total surface volume,  $VS$  ( $VS_p = 0$ ), is needed for the water to reach the end of the basin. It is only after the water reaches the basin's end that infiltration can start there. The infiltrated depth at the end of the basin will be less than  $D_{req}$ , because the

depth built up on the basin's surface during advance time is less than  $D_{\text{req}}$ , the reason being that during the period from  $T_{\text{co}}$  until  $T_a$ , part of the volume,  $VS_a$ , infiltrates farther upstream.

## A4 First-shot modes

Modes 1 and 2 both figure as first shots, as explained in Chapter 5, Section 1.4. The results are designed to be used in Modes 3 and 4, which are the core modes of BASDEV. Modes 1 and 2 use the calculation procedure of Mode 3. Mode 1 starts with a fixed value for  $Q$  and repeats the calculations with other values of  $Q$  until the application efficiency is between certain limits. These limits depend on the soil infiltration characteristics. The program calculates the corresponding infiltration time,  $T_{\text{req}}$ , for the given  $D_{\text{req}}$ ,  $A$ , and  $k$ . For this purpose, three groups are distinguished within the program, characterised by different  $T$  values, and each group is set a minimum  $E_a$  value as follows:

- Light soils:  $T < 4000 \text{ min}$   $E_a > 0.70$
- Medium soils:  $4000 < T < 23000$   $E_a > 0.80$
- Heavy soils:  $23000 < T$   $E_a > 0.90$

When you select Modes 1 or 2, BASDEV proceeds as follows:

- It calculates the value of  $T$  for given input.
- It makes an initial run in Mode 3, using  $Q = 20 \text{ l/s}$  as a starting value in Mode 1 and  $L = W = 40 \text{ m}$  in Mode 2.
- It then compares the resulting  $E_a$  with the minimum value for the calculated  $T$  as listed above.

If the value of  $E_a$  is higher than the minimum value, BASDEV takes the first default output values ( $Q = 20 \text{ l/s}$  or  $L = W = 40 \text{ m}$ ). If the value of  $E_a$  is still too low, the program makes one or more additional runs until an acceptable value is obtained. In this process, input values for  $Q$  or  $L$ - $W$  are adopted as follows:

- $L_2 = L_1 + \text{Fac} \times L_1$
- $Q_2 = Q_1 + \text{Fac} \times Q_1$

The initial value of the factor ( $\text{Fac}$ ) = 1. If necessary, BASDEV will subsequently halve it and/or make it negative. Mode 2 always works with a fixed  $L/W$  ratio of 1.

## A5 Model verification

The algorithm and the core calculations of BASDEV are the same as those of BASCAD, the program's precursor, which was developed in the early nineteen

eighties. Verification and testing of BASCAD took place from 1982 to 1984. Since then, all of the work done on the program has had to do with input, output, and interface. The core of the program has remained unchanged.

Sections A2 and A3 indicated that BASDEV assumes the following:

- The modified zero-inertia model with the modified Eulerian cell approach is appropriate for simulating the advance phase.
- The modified Manning equation and flow resistance coefficients are sufficiently accurate to describe the surface flow component.
- The infiltration characteristics and approximation of infiltration profiles are sufficiently accurate to describe the infiltration component
- The numerical solution procedures are sufficiently accurate to establish the volume balances.
- The simplifications of storage and the recession phase are realistic.

These assumptions are based on practical experience. Over the past decades, discussions of the zero-inertia and Eulerian cell approach have shown that this assumption is acceptable. Theory supports the accuracy of the coefficients for surface flow and also those for surface and subsurface storage. The infiltration equations that BASDEV uses are widely accepted. Indeed, most other surface irrigation programs use them too. Discussion and testing of the procedures for solving equations took place decades ago, and these procedures are now standard practice. Walker and Skogerboe (1987) summarise most of the theory on these issues and also provide key references. Finally, the assumptions that BASDEV uses in modelling the ponding and recession phases seem to yield acceptable results, as the following discussion shows.

BASCAD, the precursor of BASDEV, was not tested in the field. There were three main reasons why this was not done. The first was because of practical constraints on time, field facilities and money. The second was because the general opinion was that BRDRFLW, which *had* gone through field testing, was an acceptable alternative to BASCAD. And the third was that it was always possible to check the results obtained with BASCAD against those obtained with BRDRFLW. Strelkoff (1985) developed BRDRFLW, basing it on the zero-inertia model. Some years earlier, Strelkoff and Katopodes (1977) had discussed the theory of the zero-inertia model and justified it in detail, and Clemmens and Strelkoff (1979) had adapted the model for level basins. Moreover, Clemmens (1979) had discussed the results of field tests of the model. Some years later, Clough and Clemmens (1994) discussed the results of further tests for large level basins.

During BASCAD's development phase in the early 1980s, the program's designers made hundreds of runs with it and with BRDRFLW, using all sorts of combinations of input parameters and comparing the results. BASIN, a program developed some years later by Clemmens et al. (1995), also deals with basin irrigation, but it does not obtain its results by simulating the basin irrigation process. Instead, it obtains them by constructing graphs using the



Table A1. Comparison of results obtained with BASDEV and BRDRFLW for three soils

Input (n = 0.15)		BASDEV			BRDRFLW		
Flow rate (l/s.m)	Length (m)	T <sub>a</sub> (min)	T <sub>co</sub> (mm)	E <sub>a</sub> (%)	D <sub>min</sub> (mm)	T <sub>a</sub> (min)	E <sub>a</sub> (%)
<b>Soil 1</b> D <sub>req</sub> = 60 mm; infiltration: a = 0.74, k = 3.93 mm/min <sup>A</sup>							
1.7	50	39.9	41.9	70.1	60.5	40.7	70.1
1.25	40	39.6	45.8	69.9	60.5	40.3	70.0
0.9	30	36.4	46.8	71.2	60.6	37.0	71.4
<b>Soil 2</b> D <sub>req</sub> = 90 mm; infiltration: a = 0.72, k = 2.67 mm/min <sup>A</sup>							
2.0	100	78.0	93.3	80.4	90.6	80.1	80.3
1.25	70	73.1	103.7	81.0	91.5	74.4	81.2
0.6	40	71.3	124.0	80.7	91.5	72.3	81.0
<b>Soil 3</b> D <sub>req</sub> = 110 mm; infiltration: a = 0.65, k = 1.57 mm/min <sup>A</sup>							
0.9	140	188.0	314.8	90.6	109.9	192.9	90.5
0.6	105	184.5	354.1	90.6	111.2	188.5	90.6
0.3	65	197.0	442.9	89.7	109.9	201.1	89.5

values that BRDRFLW produces. Thus, because BASIN must often interpolate on graphs or between graphs, the results it produces can deviate slightly from those produced by BRDRFLW. To avoid these deviations, BASDEV results were compared with those of BRDRFLW and not with BASIN. Table A1 shows these comparisons for three soils.

In the early 1980s, it was not possible to input D<sub>req</sub> into BRDRFLW because this parameter was an output of the program. It was possible, however, to input T<sub>co</sub>, which was an output of BASCAD. Table A1 shows that the differences in the values of E<sub>a</sub> (which equals DU, see Chapter 3, Section 3.4) between BASCAD's successor BASDEV and BRDRFLW are irrelevant. More important are the differences in T<sub>a</sub>. The T<sub>a</sub> obtained from BASDEV tends to be 1 to 2 % shorter than the T<sub>a</sub> obtained from BRDRFLW. In addition, the D<sub>min</sub> from BASDEV is generally slightly lower than the one from BRDRFLW. If we input D<sub>min</sub> into Mode 4 of BASDEV, the resulting T<sub>a</sub> will be closer to the one from BRDRFLW. If we divide the basin length into 30 sections instead of 10, then the advance times for BASDEV will also be closer to those for BRDRFLW. (Nevertheless, we have decided to use 10 sections because we prefer a fast response of BASDEV on slower computers to the minimal increase in accuracy).

A special issue for discussion and verification is the advance length if water supply is cut off before the water has reached the end of the basin. This

advance length compared to the basin length is called the advance length ratio, ALR. BASDEV does not give results when cutoff occurs before flow has reached the end of the basin ( $ALR < 1$ ). This is not only because of the modeling approach for the ponding and recession phases, but also because it is impossible to solve the model equations with a zero inflow.

BASDEV will give a result as long as the flow front has travelled more than 90 % of the field length at the moment of cutoff ( $ALR \geq 0.90$ ). In its calculations, BASDEV then assumes that inflow continues after cutoff until the end of advance. Thus, the real infiltration at the basin end will be somewhat lower than the results indicate, and the real application efficiency somewhat higher. Nevertheless, many trial runs with BASDEV using various input combinations, and subsequent comparisons of the results with those of BRDRFLW, showed that the deviations were not significant in most cases. The same applies to the various efficiency and uniformity parameters. Moreover, when the simulation results deviated significantly, they were from an irrigation performance that was unacceptably poor in the first place. This finding agrees with the findings of Clemmens (1994), who upon analysis of the results of Wattenberg and Clyma (1989a), showed that the "90% criterion" is a practical limit for acceptable performance. see Chapter 8 for more information, including calculations.

## A6 Model schematisation

In addition to the assumptions in its algorithm and solutions, BASDEV also makes five main assumptions on the practical conditions in which basin irrigation takes place. These assumptions are:

### 1. *There is no surface runoff*

This is a reasonable assumption, but it has to be supported in the field by the presence of bunds that are high enough.

### 2. *Inflow is evenly distributed over the basin width*

BASDEV uses the unit flow concept, which means that it divides the volume of inflow by the width of the basin. This method enables the program to make two-dimensional calculations of the surface flow for a one-metre-wide strip (but only for the length and the vertical infiltration). Slight variations that occur, for instance, when siphons distribute inflow over basin width, do not matter because flow from the siphons will rapidly spread out to form a single, fairly straight front.

When flow enters the basin from one point inlet only, a head ditch can be used to make the inflow more uniform. Clemmens et al. (1995) state that without such a head ditch, the location of the point inlet will have no effect on the advance of flow over basins with a length-width ratio of less than 2. For basins

that are close to square, they recommend taking the diagonal distance as the field length and the actual basin area divided by the diagonal distance as the calculation width.

*3. Inflow is constant during the supply period*

Deliberate cutback of inflow is not necessary in basin irrigation. This type of irrigation produces no surface runoff, so the system operator tries to keep the inflow constant. In practice, fluctuations may occur for various reasons. Minor fluctuations in flow will not be a problem because their effects will level out during advance. Reddy and Clyma (1982) showed that this is also true for greater variations in flow. Wattenberger and Clyma (1989b) showed that inflow fluctuations have only a minor influence on the performance if cutoff occurs upon completion of advance. Their finding supports the earlier recommendation not to cut off inflow before the water has reached the end of the basin.

*4. Infiltration and flow resistance are uniform over the basin area*

Substantial variations in infiltration will certainly influence irrigation performance. The degree of influence will vary according to the irrigation parameters. Variations in flow resistance usually have less influence on performance. When resistance is higher than assumed, the advance time will be longer, consequently, performance will be lower. The program user can try to assess the effects for a certain situation by using a slightly different (uniform) infiltration input or resistance input.

*5. The basin's surface is level, with no undulations or slopes in any direction*

According to the SCS Engineering Handbook for level borders (USDA 1974), it is permissible to have some slope (not more than half of the maximum flow depth) running the length of the basin without having to adjust the calculations. Generally, a slightly downward slope will give a slightly better irrigation performance than the calculations predict, because, unless recession is clearly affected, the advance of the inflow will be faster. Slopes that run the width of the basin should always be avoided.

Undulations (ie, high and low spots) seriously affect irrigation performance, because the flow has to fill the low spots on the basin's surface before it can move over the higher spots. Proper land levelling can minimise undulations. Carefully levelled basins (ie, those with acceptable surface deviations of about 15 mm after laser-controlled levelling) will have a negligible influence on performance (Dedrick et al. 1982). Poorly levelled basins (ie, those with deviations of more than 40 mm) will have a major influence.

These five assumptions apply also to the BASIN program. Clemmens et al. (1995) include a similar discussion and justification of them in the program manual.

Finally, BASDEV deals only with the technical aspects of basin irrigation. In

the proper design and operation of a basin irrigation system, the program's result will only be one consideration among the many that include topography, the agricultural system, economics and sociology. Moreover, the water distribution in the tertiary unit and main system has a strong effect on field irrigation. To use BASDEV as effectively as possible, it is important to keep these points in mind.

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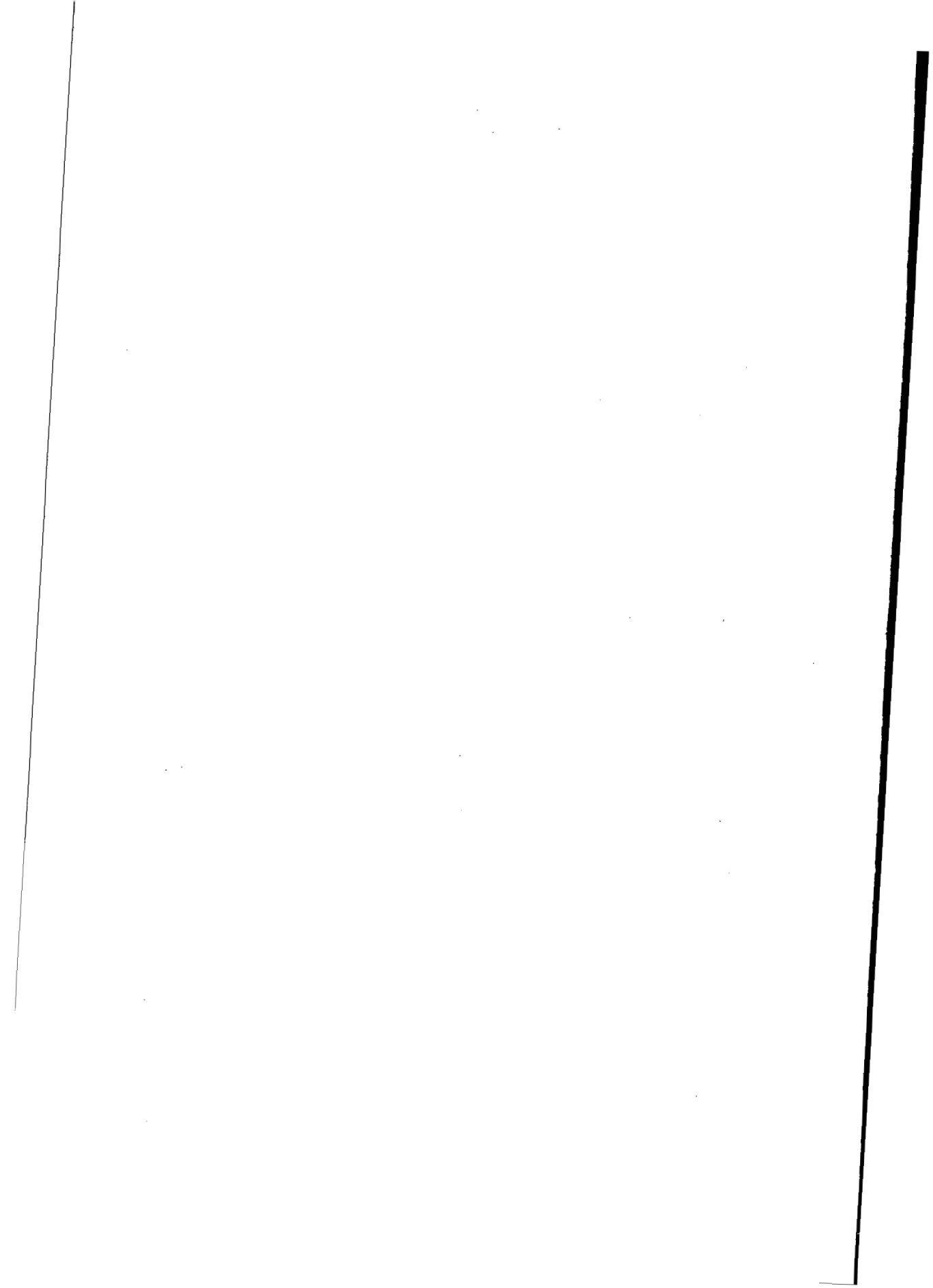


# Appendix B:

## Equations and Solution Algorithms for BORDEV and FURDEV

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# List of symbols Appendix B

$a$	Exponent in the Kostiakov-Lewis infiltration equation
$A$	Cross-sectional area
$A_L^i$	Cross-sectional area of flow at the downstream end at time step $i$
$A_o$	Inlet cross-sectional area
$A(x,t)$	Cross-sectional area of flow at $x$ and $t$
$a^m, b^m,$ $c^m, d^m$	Golden-section points
$a_1, a_2$	Coefficient and exponent of the power function for a power-law cross-section.
$a_2, b_2$	Constants that depend on furrow geometry parameters
$C_f$	Correction factor
$C_1, C_2$	Constants that depend on furrow geometry parameters $\sigma_1, \sigma_2, \tau_1, \tau_2$
$d_1, d_o$	Constants that depend on furrow geometry parameters and upstream and downstream flow depths
$D$	Infiltration depth
$D_{\min}$	Minimum infiltrated depth
$D_{\text{req}}$	Required infiltrated depth
$D_{\text{us}}$	Infiltrated depth at the upstream end
$E_a$	Application efficiency
$f_o$	Coefficient in the Kostiakov-Lewis infiltration equation
$i_T$	Infiltration rate at time $T$
$i_{T_{co}}$	Infiltration rate at cutoff at the upstream end
$i_{T_{co}-TL}$	Infiltration rate at $T_{co}$ at the downstream end
$I$	Average infiltration rate over the length of a furrow or a unit width border
$I_i$	Average infiltration rate over the length of the furrow at time step $i$
$I_{T_{co}}$	Average infiltration rate over the length of the furrow at $T_{co}$
$I_{Td}$	Average infiltration rate over the length of the furrow at the end of the depletion phase
$k$	Coefficient in the Kostiakov-Lewis infiltration equation
$l_i$	Length of the water-covered section of the furrow at time step $i$
$L$	Field length
$L_{\text{ini}}$	Initial value of the field length
$n$	Manning's roughness coefficient
$p$	Coefficient of the power-law advance function
$P$	Wetted perimeter
$P_{\text{av}}$	Average wetted perimeter
$P_l^i$	Average wetted perimeter for the water-covered section of the furrow at time step $i$
$P_{\text{max}}$	Wetted perimeter at $T_{co}$

$P_1, P_2$	Wetted perimeter values corresponding to $(Y_1, T_1)$ and $(Y_2, T_2)$ , respectively
$Q_o$	Flow rate at the inlet
$Q_{av}^i$	Average runoff rate between time steps $i$ and $i+1$ during recession
$Q_L^i$	Runoff rate at the downstream end at time step $i$
$Q_{max}$	Maximum non-erosive flow rate
$Q_{min}$	Minimum flow rate to just reach the end of the field
$Q_R   T_{co}$	Runoff rate at $T_{co}$
$Q_s$	Minimum unit flow rate required for adequate spread
$r$	Exponent of the power-law advance function
$r^j$	Exponent of the power-law advance function at step $j$
$r_1, r_2$	Golden-section constants
$R$	Hydraulic radius
$S$	The search interval containing all the feasible points
$S_o$	Bed slope
$S_y$	Water surface slope during recession
$t$	Time
$T$	Intake opportunity time
$T$	Top width of the water in a furrow
$T_{co}$	Cutoff time
$T_d$	Depletion time
$T_d(1)$	Initial estimate of the depletion time
$T_d(2)$	Revised estimate of the depletion time
$T_{lag}$	Depletion time
$T_L$	Advance time to the downstream end
$T_L^j$	Advance time to the downstream end at step $j$
$T_{0.5L}$	Advance time to halfway the downstream end
$T_{0.5L}^j$	Advance time to halfway the downstream end at step $j$
$T_{max}$	Maximum top width
$T_r$	Recession time
$T_r(X)$	Recession time at distance $X$
$T_{req}$	Time required to infiltrated the required depth
$T_x$	Advance time to a point at $x$ metres from the inlet end
$T_x^i$	Advance time to a point at $x$ metres from the inlet end at step $i$
$T_1, T_2$	Top width values used to calculate $P_1$ and $P_2$
$V_{co}$	Volume of water under surface storage at $T_{co}$
$V_d$	Wedge-shaped volume of water that is removed from surface storage during the depletion phase
$V_{max}$	Maximum non-erosive velocity
$V_{rm}^i$	Volume removed from surface storage between time steps $i$ and $i-1$
$V_{ss}(l_i)$	Volume of water under surface storage at the $i^{th}$ time step during recession
$W$	Furrow bed width
$W_f$	Furrow spacing

$x$	Decision variable, which could be $Q_0$ or $L$ depending on the calculation mode
$x^l, x^u$	Lower and upper bounds of the decision variable
$X$	Advance distance
$Y$	Flow depth
$Y_L$	Flow depth at the downstream end of a furrow during depletion and recession
$Y_{\max}$	Maximum flow depth
$Y_0$	Flow depth at the head end of a furrow during depletion and recession
$Y_1, Y_2$	Flow depths used to calculate $P_1$ and $P_2$
$z$	Side slope of a triangular or trapezoidal furrow cross-section
$Z(x, t)$	Cumulative infiltration expressed as volume per unit length at $x$ and $t$
$\Delta T_{\text{rec}}^i$	Time required for the receding tip to travel from $l^i$ to $l^{i+1}$
$\Delta X_i$	The $i^{\text{th}}$ distance interval
$\sigma_y$	Surface storage shape factor
$\sigma_z, \sigma_z'$	Subsurface storage shape factors
$\sigma_1, \sigma_2$	Furrow geometry parameters that relate cross-sectional area with depth
$\tau_1, \tau_2$	Furrow geometry parameters that relate wetted perimeter with depth
$\varepsilon_{\text{fbc}}, \varepsilon_{\text{bc}}$	Error tolerance limits



## B1 Introduction

This appendix explains the major computational procedures of the BORDEV and FURDEV programs. Both packages are based on existing theories and therefore we decided not to present all the details here. What we have done is indicate the broad outlines and refer the interested reader to the relevant literature for further details. Because the core of the BORDEV and FURDEV programs are based on the same principles, they are discussed together in one appendix. Differences are indicated and explained where relevant.

We have used different approaches to simulate the various phases (advance, ponding, depletion and recession). For instance, the volume balance method has been used in both programs to simulate the advance phase. The details of this approach can be found in Walker and Skogerboe (1987) and in Walker (1989). To simulate the ponding, depletion and recession phases, simple algebraic approaches have been used as originally discussed in Strelkoff (1977).

Two things make the calculations for furrows more complicated than that for borders (and basins). One concerns the geometry of the surface flow. Furrows have complicated cross sections (see Section B5), whereas borders have simple, very wide, rectangular sections. The second complication in furrow modelling is that water infiltrates in various directions along the wet section of the furrow, whereas borders only have vertical infiltration. Also, furrow calculations are done with the furrow spacing instead of the unit width of one metre for basins and borders.

We shall discuss the advance phase first (in Section B2), which has the same equations and procedures in both FURDEV and BORDEV. Then follow the approaches used for the ponding, depletion and recession phases for FURDEV (in Section B3) and for BORDEV (in Section B4). Furrow geometry factors are discussed in Section B5, followed by a description of the optimisation procedure for the application efficiency (in Section B6).

## B2 Advance phase

### B2.1 Basic equations

To search for the distribution of the infiltrated depths along the border or furrow, we use the infiltration advance model that is based on three equations. The first relates the advance of the water front in the furrow to the elapsed time according to an empirical power law which can be written as

$$X = pT_x^r \quad (\text{B.1})$$

in which

$x$  = distance that the water front has travelled along the furrow (m)

$T_x$  = elapsed time since water was let into the furrow (min)  
 $p, r$  = empirical fitting parameters

Water infiltrates over the wetted distance as the water front advances, according to the modified Kostiakov-Lewis infiltration equation, which is the second equation in the infiltration-advance model

$$D = kT^a + f_0T \quad (B.2)$$

in which

$D$  = cumulative infiltration (mm)  
 $T$  = intake opportunity time (min)  
 $k, a, f_0$  = empirical fitting parameters

These two equations are linked by the factor time: at a certain elapsed time,  $T_x$  in Equation B1, the intake opportunity time at the upstream end,  $T$  in Equation B2, are the same. Once both relationships are defined, one can determine the infiltrated depth at any distance along the furrow or border during the advance phase. When the wetting front reaches the end of the field (where  $x = L$ ),  $T_x$  equals the duration of the advance phase,  $T_L$ . In a normal design situation we know the fitting parameters of the infiltration equation, but we do not know those of the advance equation, ie, we would want to determine  $T_L$ , but do not know  $p$  and  $r$ . To solve this problem, we can use the continuity or volume balance equation (the third basic equation in the infiltration advance model), which reads

$$Q_0T_x = \int_0^x A(x, t)dx + \int_0^x Z(x, t)dx \quad (B.3)$$

where

$Q_0$  = flow rate at the inlet boundary  
 $A(x, t)$  = cross-sectional area of surface flow, variable with distance and time  
 $Z(x, t)$  = cross-sectional area of infiltrated water, variable with distance and time

This equation is called the volume balance equation because the left-hand side represents the total inflow volume over time  $T_x$ , which should equal the surface storage volume, the first integral, plus the infiltrated volume, the second integral. If one writes

$$\int_0^x A(x, T)dx = \sigma_y A_0 X \quad (B.4)$$

where

$A_o$  = inlet cross-sectional area

$\sigma_y$  = surface-storage shape factor

and we insert the right-hand side of Equation B.4 into Equation B.3, the latter changes into the Lewis and Milne (1938) form of the volume balance equation. Assuming that as inflow starts the water level at the inlet immediately rises to a constant normal depth,  $A_o$  remains constant. However, the water surface dips towards the wetting front, and the average cross-section over  $X$  equals  $\sigma_y A_o$ . This reduction factor is often found to be 0.7-0.8. FURDEV and BORDEV use  $\sigma_y = 0.77$ .

Manning's equation and some flow geometry coefficients are used to calculate  $A_o$  from

$$A_o = C_1 \left( \frac{Q_o n}{60 S_o^{0.5}} \right)^{C_2} \quad (B.5)$$

in which

$n$  = Manning's roughness coefficient

$S_o$  = bed slope

$C_1, C_2$  = geometry constants

The factor 60 accounts for  $Q_o$  being expressed in  $m^3/min$ , as commonly used in American theory of the volume balance model, instead of  $m^3/s$ .

The two geometry constants can be computed from values of  $\sigma_1, \sigma_2, \tau_1$ , and  $\tau_2$ , which are detailed in Section B5. The equations for  $C_1$  and  $C_2$  are

$$C_1 = \sigma_1 \left( \frac{\tau_1^{0.67}}{\sigma_1^{1.67}} \right)^{C_2} \quad (B.6)$$

and

$$C_2 = \frac{3\sigma_2}{5\sigma_2 - 2\tau_2} \quad (B.7)$$

Note, these values are important for furrows, ie, in the FURDEV model. In BORDEV, with its simpler flow geometry,  $\sigma_1 = \sigma_2 = \tau_1 = 1.0$  and  $\tau_2 = 0$ .

The infiltrated volume can be expressed as (Christiansen et al. 1966)

$$\int_0^x Z(x, T) dx = \sigma_z k T_x^a + \sigma_z' f_0 T_x X \quad (B.8)$$

in which  $\sigma_z$  and  $\sigma_z'$  are subsurface-storage shape factors. According to Kiefer (1959), an approximate expression for the factor  $\sigma_z$  is

$$\sigma_z = \frac{a + r(1 - a) + 1}{(1 + a)(1 + r)} \quad (B.9)$$

and  $\sigma_z'$  equals

$$\sigma_z' = \frac{1}{1 + r} \quad (B.10)$$

Taking all elements of the volume balance together, we obtain

$$Q_0 T_x - 0.77 A_0 X - \sigma_z k T_x^a X - \sigma_z' f_0 T_x X = 0 \quad (B.11)$$

This equation forms the basis of the advance phase calculations in the FURDEV and BORDEV programs. Given  $Q_0$  and  $X$ , Equation B.11 is to be solved for  $T_x$ . The other parameters in Equation B.11 are also given, except the power  $r$  of the advance equation, which appears in Equations B.9 and B.10.

## B2.2 Solution

Equation B.11 is a non-linear equation with two unknowns, ie,  $T_x$  and  $r$ . According to Walker and Skogerboe (1987), values for these two unknowns can be derived using a two-stage iterative procedure. The procedure is explained in detail in Walker and Skogerboe (1987, p.141) as well as in Walker (1989, p.69), and will only be summarised here. The essence of the procedure consists of two iterative loops, as illustrated in Figure B.1. The inner loop forms the core of the algorithm, in which, for a "given" value of  $r$  (starting value  $r = 0.5$ ), the advance time to the mid-distance point,  $T_{0.5L}$ , (using  $X = L/2$ ) and to the downstream end,  $T_L$ , (using  $X = L$ ) are calculated iteratively. The starting value for  $T_x$  is found from

$$T_x = \frac{5A_0 X}{Q_0} \quad (B.12)$$



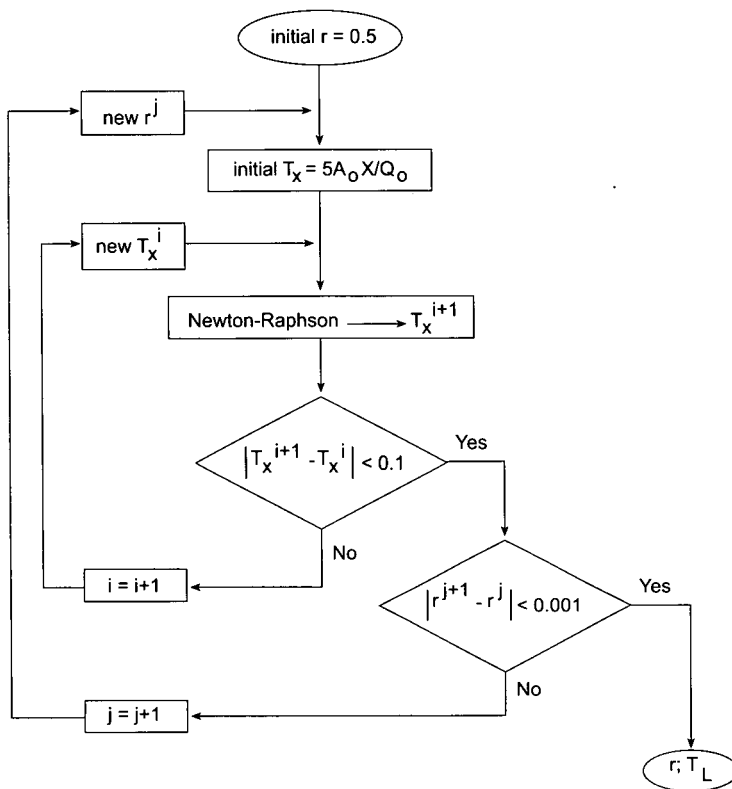


Figure B.1 Inner and outer loops to find  $r$  and  $T_L$

Then, the Newton-Raphson iteration method (see, for example, Walker and Skogerboe 1987) is used to find the next value of  $T_x$ , ie, by applying

$$T_x^{i+1} = T_x^i - \frac{f(T_x)}{f'(T_x)} \quad (\text{B.13})$$

In our case this yields

$$T_x^{i+1} = T_x^i - \frac{Q_o T_x^i - 0.77 A_o X - \sigma_z k(T_x^i)^a X - \sigma'_z f_o T_x^i X}{Q_o - a \sigma_z k(T_x^i)^{a-1} X - \sigma'_z f_o X} \quad (\text{B.14})$$

The inner loop ends if  $|T_x^{i+1} - T_x^i| < 0.1$  min and  $T_x$  equals  $T_{0.5L}$  or  $T_L$ . The outer loop calculates  $r$  iteratively. As mentioned above, the starting value is 0.5, but after calculating  $T_{0.5L}$  and  $T_L$ , a revised estimate of  $r$  is found as follows

$$r^{j+1} = \frac{\ln(2)}{\ln\left(\frac{T_L^j}{T_{0.5L}^j}\right)} \quad (\text{B15})$$

If  $|r^{j+1}-r^j| \leq 0.001$ , the calculation is concluded and we have found both  $r$  and  $T_L$ . By using Equation B.1 we find  $p = L/T_L^r$  and the advance equation is known. It is now possible to find the infiltrated depth along the whole border or furrow length for the end of the advance phase.

### B2.3 Assumptions and limitations

Equation B.5 assumes that flow depth at the inlet boundary instantaneously rises to a normal depth and that for any given flow rate and system parameters combination, the average flow depth remains constant during the advance phase, irrespective of advance distance and time. In deriving Equation B.11 from Equation B.3, the following are implicitly assumed:

1. The flow rate is constant during the advance phase.
2. The soil is homogeneous throughout the length of run of the border or furrow.
3. Manning's channel roughness coefficient is constant.
4. The flow channel is prismatic.
5. Cutoff time is greater than advance time.

## B3 Ponding, depletion and recession in FURDEV

### B3.1 Ponding

Water continues to infiltrate during the ponding phase. To ascertain how much water infiltrates at various points along the furrow, we need to know the duration of the ponding phase. The ponding phase begins at the end of the advance phase,  $T_L$ , and ends at the cutoff time,  $T_{co}$ . In FURDEV, cutoff time is either given as an input variable (in Calculation Mode 4) or must be calculated (in Calculation Modes 1, 2 and 3, where  $D_{min} = D_{req}$ ). This means that in Calculation Mode 4 the duration of the ponding phase is fixed and is  $T_{co}-T_L$ .

The cutoff time is found iteratively in Modes 1, 2 and 3. A first estimate of  $T_{co}$  is made and the depletion and recession times are calculated resulting in a revision of the first estimate of  $T_{co}$ , etc. The first estimate of  $T_{co}$  is obtained from

$$T_{co}^1 = T_L + T_{req} \quad (B.16)$$

where

$T_L$  = advance time to the downstream end point (min)

$T_{req}$  = required intake-opportunity time to infiltrate  $D_{req}$  (min)

Then, based on this first estimate, the depletion and recession phases are simulated as outlined below, whereby  $D_{min}$  is calculated. If  $D_{min}$  is virtually equal to  $D_{req}$ , then the calculation of  $T_{co}$  is concluded. If not, a new estimate of  $T_{co}$  is made and so on.

### B3.2 Depletion

During depletion and recession, both infiltration and runoff occur and to be able to quantify both, we must know the duration of the two phases. We use the approach suggested by Strelkoff (1977) for border irrigation, modified and elaborated for furrow irrigation by Ley (1978) and Essafi (1983), as outlined in Walker and Skogerboe (1987). Assumptions for the depletion phase, according to the Strelkoff model, are (see Figure B.2):

1. The sum of infiltration and runoff after cutoff continues to equal the pre-cutoff inflow,  $Q_0$ .
2. At the time of cutoff, the surface-water profile is a straight line.
3. Water depths at both ends correspond with uniform flow.
4. During depletion, the downstream outflow (runoff) and depth remain constant; the upstream depth decreases to zero at the end of depletion.

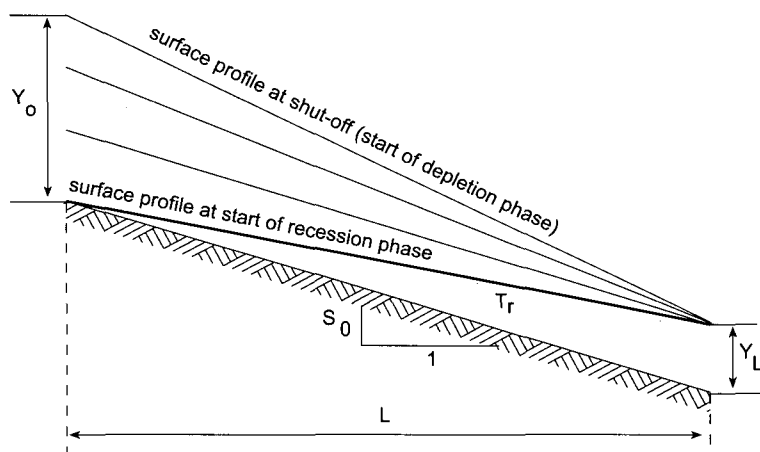


Figure B.2 Depletion phase assumptions

The depletion time,  $T_d$ , equals the sum of  $T_{co}$  and the duration of the depletion period, sometimes called  $T_{lag}$ .  $T_{lag}$  is the time it takes the upper end to fall dry after cutoff. It is found by dividing the volume removed during depletion by the removal rate following assumption 1, according to:

$$T_{lag} = \frac{V_d}{Q_0} \quad (B.17)$$

Next, we calculate the wedge-shaped volume of water,  $V_d$  ( $m^3$ ), that can be removed from the furrow during the depletion phase (Figure B.2) using the following approximate expression

$$V_d = 0.23V_{co} \quad (B.18)$$

where 0.23 equals  $1 - \sigma_y$ , with  $\sigma_y$  the surface shape factor, which is taken as 0.77 in FURDEV.  $V_{co}$  is the volume of water under surface storage at  $T_{co}$  ( $m^3$ ). Thus, 23 % of  $V_{co}$  leaves the field during the depletion phase, as opposed to the 50 per cent assumed for borders. Evidently, this is an approximation which appears to work satisfactorily. Now, according to Ley (1978), we express  $V_{co}$  as

$$V_{co} = 2L \left( \frac{Y_L d_1 + Y_o d_o}{3} + \frac{Y_L d_1 + Y_L d_o}{6} - \frac{a_2}{b_2 + 1} d_o^{b_2 + 1} \right) \quad (B.19)$$

where

$$d_o = \frac{\sigma_1 \sigma_2}{2} Y_o^{\sigma_2 - 1}, d_1 = \frac{\sigma_1 \sigma_2}{2} Y_L^{\sigma_2 - 1}, b_2 = \frac{1}{\sigma_2 - 1}, a_2 = \left( \frac{2}{\sigma_1 \sigma_2} \right) \quad (B.20)$$

in which  $\sigma_1$  and  $\sigma_2$  are furrow geometry factors (Section B5) and  $Y_o$  and  $Y_L$  are the water depths at the head and at the tail of the furrow, respectively, at cut-off. Because of the assumed normal depths at both ends, these water depths are known via the geometry relation  $A = \sigma_1 Y^{\sigma_2}$  and the Manning expression for  $A$  as used in Equation B.5. The  $Y_L$  is found from  $Q_{R|T_{co}}$ , the runoff rate during the depletion phase

$$Q_{R|T_{co}} = Q_0 - I_{T_{co}} L \frac{P_{av}}{W_f} \quad (B.21)$$

in which the infiltration term equals the average of the rates at the beginning

and the end of the furrow

$$I_{T_{co}} = \frac{i_{T_{co}} + i_{T_{co}-T_L}}{2} \quad (B.22)$$

and for i we can use the instantaneous form of the Kostiakov-Lewis equation

$$i_T = a k T^{a-1} + f_0 \quad (\text{B.23})$$

The expression  $LP_{av}/W_f$  in Equation B.21 indicates the infiltrating area (corrected for the furrow width,  $W_f$ ), being the product of the furrow length,  $L$ , and the average wet perimeter,  $P_{av}$ . The latter is derived from the average wet area  $\sigma_y A_o$ , which gives the water depth and the wet perimeter using the geometry factors  $\sigma_1$ ,  $\sigma_2$ ,  $\tau_1$  and  $\tau_2$ .

We thus find  $T_{lag}$ , applying Equation B.17, and so  $T_d = T_{co} + T_{lag}$ . The infiltration opportunity time along the furrow at the end of the depletion phase is then  $T_d$  at the furrow head, and  $T_d - T_L$  at the tail, and  $T_d - T_x$  in between. The only remaining item we need to know in order to define the final infiltration distribution is the recession time.

### B3.3 Recession

Simplified assumptions have been introduced by Strelkoff (1977) and later by Ley (1978) to create algebraic equations to solve the recession problem:

- Water surface profiles during the recession phase are straight lines parallel to the water surface profile at the end of the depletion phase (see Figure B.3).
- At any instant during recession, flow depth at the downstream end is normal for the corresponding flow rate.

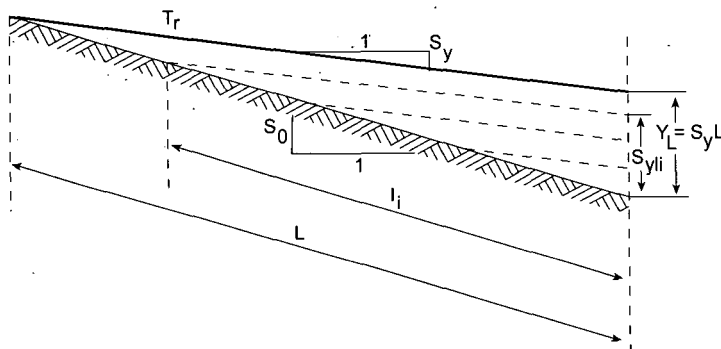


Figure B.3 Recession phase assumptions

The value of  $T_r$  varies with the distance along the furrow,  $X$ . The array of points,  $(X, T_r(X))$ , that define the recession trajectory are calculated using a recursive procedure, in which the receded distance is fixed as multiples of  $L/24$ , and the time required for the receding edge to trail to that point from an adjacent point is calculated as  $T_r(X)$ . This recession time follows from the removed volume of water between two steps, divided by the average removal rate.

The procedure starts with determining the volume of water under surface storage at any given time during recession,  $V_{ss}$  ( $m^3$ ), as a function of the water-covered length of the furrow. This length equals

$$l^i = L - \sum \Delta X_i \quad (B.24)$$

Looking at Figure B.3, we can see that the water depth at the lower end is equal to the slope of the water surface,  $S_y$ , multiplied by this  $l^i$ . This slope is found by dividing the water depth at the lower end at the end of the depletion phase by furrow length,  $L$ . Using  $A = \sigma_1 Y^{\sigma_2}$ , and substituting  $Y = S_y \cdot l^i$ , we find  $V_{ss}$  as the distance integral of  $A$  as follows

$$V_{ss}(l^i) = \frac{\sigma_1 S_y^{\sigma_2} (l^i)^{\sigma_2 + 1}}{\sigma_2 + 1} \quad (B.25)$$

The volume of water under surface storage at the end of the depletion phase equalled  $V_{co} - V_d$ , which volume equals  $V_{ss}$  at the start of the recession phase, when the whole furrow is still wet. To force this, a correction factor,  $C_f$ , needs to be applied

$$C_f = \frac{V_{co} - V_d}{V_{ss}(L)} \quad (B.26)$$

The difference between  $V_{ss}$  at moment  $i$  can be subtracted from that at  $i-1$  to give the removed volume,  $V_{rm}^i$ .

Now we still need to determine the removal rate for each volume. This rate has a runoff term and an infiltration term. For each step  $i$ , the runoff rate is calculated using Manning's equation, or

$$Q_L^i = \frac{60 S_o^{0.5}}{n} \left( \frac{A_L^i}{C_1} \right)^{\frac{1}{C_2}} \quad (B.27)$$

and the average  $Q_{av}^i$  is then easily found from  $Q_L^i$  and  $Q_L^{i-1}$ . As usual, the cross-sectional area at the downstream end is found from  $\sigma_1 (l^i S_y)^{\sigma_2}$ .

The average infiltration rate is found from two adjacent rates at  $i$  and  $i-1$ . One such rate,  $I_i$ , is calculated using the ratio of  $P_1^i$  and  $P_{\max}$  (Ley 1978).

$$I_i = I_{T_d} \frac{P_1^i}{P_{\max}} l_i \quad (\text{B.28})$$

where

$I_{T_d}$  = the average infiltration rate at  $T_d$  and  $T_d - T_L$ , equivalent to Eq. B.22, with  $T_d$  replacing  $T_{co}$

$P_1^i$  = the average wetted perimeter for the water-covered length of the furrow

$P_{\max}$  = wetted perimeter at  $T_{co}$

We find  $P_{\max}$  from

$$P_{\max} = \tau_1 \left( \frac{Y_o + Y_L}{2} \right)^{\tau_2} \quad (\text{B.29})$$

where  $\tau_1$  and  $\tau_2$  are geometry factors (Section B5). In FURDEV  $P_1^i$  is calculated as follows: (i) the equation of the wetted perimeter is integrated over  $l^i$  numerically, using the composite trapezoidal rule for 14 intervals and (ii) the quantity thus obtained is then divided by  $l^i$  and is adjusted by multiplying it by  $C_f$  (Walker and Skogerboe 1987). The time required for the receding edge to travel from  $l^i$  to  $l^{i+1}$  can be derived from the following equation

$$\Delta T_{\text{rec}}^i = \frac{V_{\text{rm}}^i}{Q_{\text{av}}^i + I_i} \quad (\text{B.30})$$

If we add these time intervals from the start of recession, we obtain the recession time  $T_{\text{rec}}$  at various stations along the furrow in minutes, the maximum value being  $T_{\text{rec}}(L)$  at the downstream end of the furrow. If we add this maximum to  $T_d$ , we get the recession time  $T_r$ , marking the end of the irrigation.

Having computed depletion and recession times, we now remember that when we started the ponding phase we assumed a value for  $T_{co}$  in Calculation Modes 1-3. To check if this assumption was satisfactory, we first calculate  $D_{\min}$  by looking at the infiltrated depth at the upstream and the downstream ends and calling the minimum value  $D_{\min}$ . If this  $D_{\min}$  differs by more than  $0.001D_{\text{req}}$  from  $D_{\text{req}}$ , we need a revised estimate of  $T_{co}$  and the whole procedure of the depletion and recession computations is repeated to finally get a revised value of  $D_{\min}$  that satisfies the condition that  $D_{\min}$  must be virtually equal to  $D_{\text{req}}$ .

For the 25 points along the furrow we can now determine the infiltrated amounts by first finding the infiltration opportunity time at each point. We use the cutoff time and the advance function to give values of  $T_{co}-T_x$ , add values of the depletion time (or lag time,  $T_{lag}$ ) and also add the recession times,  $T_{rec}$ . This will allow us to calculate the infiltrated depths along the furrow length.

#### B4 Ponding, depletion and recession in BORDEV

The BORDEV algorithm relating to the ponding, depletion and recession phases follows the theory as developed by Strelkoff (1977) and summarised in Walker and Skogerboe (1987). Different approaches are followed for Modes 1-3 and Mode 4. In Modes 1-3 the cutoff time is calculated such that the minimum infiltrated depth will be equal to the required depth (Case 2 below). In Mode 4 this is not the case and  $T_{co}$  is given as input (Case 1 below). The last-mentioned approach is discussed first because it is the more straightforward one.

Case 1. In this case (calculation Mode 4),  $T_{co}$  is part of the input data so it is impossible to enforce the requirement  $D_{min} = D_{req}$ . The procedure is to first calculate the depletion time  $T_d$  and then the recession time  $T_r$  can be calculated. The depletion time  $T_d$  is determined with Equation B.31

$$T_d = T_{co} + \frac{Y_o L}{2Q_o} \quad (B.31)$$

where  $Y_o$  = depth of flow at the inlet, according to Equation B.5.

The recession time  $T_r$  is then calculated as

$$T_r(X) = T_d + \frac{0.095 n^{0.47565} (S_y)^{0.20735} X^{0.6829}}{(I)^{0.52435} S_o^{0.237825}} \quad (B.32)$$

In this,  $I$  is the average infiltration rate over the border length, which is a function of the prevailing value of  $T_d$ , as

$$I = akT_d^{a-1} L - \frac{a(a-1)kT_d^{a-2} T_L L}{r+1} + \frac{ak(a-1)(a-2)T_d^{a-3} T_L^2 L}{2(2r+1)} - \frac{a(a-1)(a-2)(a-3)kT_d^{a-4} T_L^3 L}{6(3r+1)} + f_o L \quad (B.33)$$



and  $S_y$  is the water surface slope, determined as

$$S_y = \frac{1}{L} \left( \frac{(Q - IL)n}{60 S_o^{0.5}} \right)^{0.6} \quad (B.34)$$

The use of  $T_d$  in Equation B.33 assumes that the variation in the intake rate of the soil during the recession phase is negligibly small. This is a plausible assumption. As all necessary parameters are known, the infiltrated depths over the border length can now be calculated.

Case 2. Here the condition that  $D_{\min} = D_{\text{req}}$  is to be enforced (Calculation Modes 1-3). Core of the procedure is again the determination of the depletion time  $T_d$ . Using Equation B.31 the cutoff time  $T_{\text{co}}$  can then be determined. The calculation of  $T_d$  involves an iteration process whereby the following equation is used, which equation is similar to Equation B.32.

$$T_d(2) = T_d(1) + \frac{0.095n^{0.47565} (S_y) X^{0.6829}}{(I)^{0.52435} S_o^{0.237825}} \quad (B.35)$$

In this, a first estimate  $T_d(1)$  must be made, for which we take  $T_d(1) = T_r(L)$ , the latter being found as  $T_r(L) = T_{\text{req}} + T_L$ , where  $T_L$  is the advance time (this first estimate  $T_d(1)$  in fact is the recession time, assuming that the minimum infiltrated depth occurs at the downstream end of the border). Summarising, the procedure runs as follows:

1. Let  $T_d(1) = T_r(L)$ , where  $T_d(1)$  is the initial estimate of  $T_d$
2. Calculate  $T_d(2)$ , a revised estimate of  $T_d$ , using Equation B.35
3. As long as  $|T_d(2) - T_d(1)| > 0.1$ , then redo the above step b with  $T_d(1) = T_d(2)$
4. When  $|T_d(2) - T_d(1)| < 0.1$ , the depletion time  $T_d$  equals  $T_d(2)$

Now, check that there is no under-irrigation at the upstream end of the border by calculating  $D_{\text{us}}$  with the Kostiakov-Lewis equation as

$$D_{\text{us}} = kT_d^a + f_o T_d \quad (B.36)$$

If the assumption was correct we can now calculate  $T_{\text{co}}$  with Equation B.31. If the assumption was not correct and under-irrigation appears to occur at the upstream end:

5. Set  $T_d = T_{\text{req}}$  and solve Equation B.31 for  $T_{\text{co}}$
6. Calculate  $I$  and  $S_y$  using Equations B.33 and B.34, respectively

As with Case 1, now that all the necessary parameters are known the infiltrated depths along the length of the border can be calculated.

## B5. Furrow geometry parameters

Furrow geometry is an important input in the modelling of the furrow irrigation process. There are three geometric elements that have a direct bearing on the surface hydraulics, infiltration and soil erosion in open channels:

- Cross-sectional area of flow,  $A$ , is required to estimate surface storage and flow velocity
- Wetted perimeter,  $P$ , affects the infiltration
- Hydraulic radius,  $R$ , is needed to calculate the flow resistance

These geometric elements of a channel are functions of flow depth,  $Y$ , and the geometry of the section. Hydraulic channels are often prismatic, but furrows rarely are and mostly have an irregular cross-section. Moreover, the original furrow cross-section often changes in the course of the season due to the irrigation stream. The cross-sectional shapes of newly formed furrows can vary from triangular to trapezoidal. The eventual hydraulically-stable shape is dependent on the soil physical properties as well as on the magnitude and distribution of the shear force (Chow 1959). Many researchers have assumed that the final stable geometric shape obeys some kind of power law (Fangmeier and Ramsey 1978; Elliott et al. 1982; Walker and Skogerboe 1987), such as Equation B.37, which relates the top width of the water in the furrow,  $T$ , to the water depth,  $Y$

$$T = a_1 Y^{a_2} \quad (\text{B.37})$$

where

$T$  = top width of flow

$Y$  = depth of flow

$a_1$  and  $a_2$  = coefficient and exponent of the power function, respectively

The wet cross-sectional area,  $A$ , can be derived by integrating Equation B.37 over  $Y$ , producing

$$A = \sigma_1 Y^{\sigma_2} \quad (\text{B.38})$$

where the furrow-geometry parameters  $\sigma_1$  ( $\text{m}^{2-\sigma_2}$ ) and  $\sigma_2$  (-) are given as

$$\sigma_1 = \frac{a_1}{a_2 + 1} \quad \text{and} \quad \sigma_2 = a_2 + 1 \quad (\text{B.39})$$

The exact expression for the wetted perimeter,  $P$  (m), of a power law cross-section is

$$P = 2 \int_0^Y \sqrt{1 + a_1^2 a_2^2 Y^{2(a_2 - 1)}} dy \quad (B.40)$$

A closed-form solution of Equation B.40 is available only for parabolic ( $a_2 = 0.5$ ) and triangular ( $a_2 = 1$ ) sections, which are particular cases of power law cross-sections. The  $P$  of a power law cross-section can, however, be well approximated as a power function of the flow depth, as in Equation B.41, (Elliott et al. 1982; Fangmeier and Ramsey 1978).

$$P = \tau_1 Y^{\tau_2} \quad (B.41)$$

where  $\tau_1$  ( $m^{1-\tau_2}$ ) and  $\tau_2$  (—) are additional furrow-geometry parameters. Kessira (1996) has shown that the maximum relative error that could occur from the use of Equation B.41 for a range of flow conditions is less than, or equal to, 10 per cent. It is a simple matter to derive an expression for  $R$  as a function of  $Y$  and the geometry parameters using Equations B.38 and B.41. For reasons of simplicity, FURDEV uses these two equations to estimate the wetted area and wetted perimeter of a trapezoidal cross-section as well. Below, we describe the relationships between the dimensions of the flow cross-section and the furrow-geometry parameters for the three standard geometric sections that can be selected in FURDEV, ie, triangular, trapezoidal and parabolic.

#### Triangular cross-section

The type of cross-section which is of concern here is a symmetric triangular cross-section. Based on the geometry of a triangle and the assumed power law relationships between  $A$  and  $P$  on the one hand and  $Y$  on the other (Equations B.38 and B.41), the geometry parameters corresponding to a triangular cross-section are given as

$$\sigma_1 = z, \sigma_2 = 2, \tau_1 = 2\sqrt{(z^2 + 1)}, \tau_2 = 1 \quad (B.42)$$

where  $z$  = side slope

#### Trapezoidal cross-section

The cross-sectional area and wetted perimeter of a trapezoidal cross-section cannot be expressed as an exact power law of depth. Thus, any estimate of area and wetted perimeter of a trapezoidal section using Equations B.38 and B.41 is an approximation. Optimal geometry parameters can be determined by regressing area and wetted perimeter against flow depth. A simple, but less accurate, approach involves the use of a pair of  $Y$ s and associated  $A$ s and  $P$ s to form a pair of equations, for both  $A$  and  $P$ , which can then be logarithmi-

cally transformed and solved simultaneously for the unknown geometry parameters. Kessira (1996) has shown that for any given cross-section and range of flow depths there is a unique pair of flow depths to minimise error. This approach has been implemented in FURDEV. The program uses an arbitrarily selected maximum flow depth of 0.20 m to calculate two depth values,  $Y_1 = 0.6Y_{\max} = 0.12$  m and  $Y_2 = 0.3Y_{\max} = 0.06$  m. Based on these values of  $Y_1$  and  $Y_2$  and the user-specified bed width,  $W$ , and side slope,  $z$ , FURDEV calculates the parameters of Equations B.38 and B.41 using Equations B.43-B.47

$$\sigma_1 = \frac{WY_1 + zY_1^2}{Y_1^{\sigma_2}} \quad (\text{B.43})$$

$$\sigma_2 = \frac{\log \frac{WY_1 + zY_1^2}{WY_2 + zY_2^2}}{\log \frac{Y_1}{Y_2}} \quad (\text{B.44})$$

$$\tau_1 = \frac{W + (2\sqrt{1+z^2})Y_1}{Y_1^{\tau_2}} \quad (\text{B.45})$$

$$\tau_2 = \frac{\log \frac{W + (2\sqrt{1+z^2})Y_1}{W + (2\sqrt{1+z^2})Y_2}}{\log \frac{Y_1}{Y_2}} \quad (\text{B.46})$$

### Parabolic cross-section

A parabola is a special case of a power law. The values of  $\sigma_1$  and  $\sigma_2$  for a power law cross-section are given in Equation B.38. For a parabola, where  $y$  varies with  $T^2$ , we easily see that the power  $a_2 = 0.5$ , hence  $\sigma_2 = 1.5$ . For known values of  $T_{\max}$  and  $Y_{\max}$  (which are entered on the screen, default values being 0.5 m and 0.2 m, respectively) we find coefficient  $a_1$  as  $T_{\max}/\sqrt{Y_{\max}}$  therefore

$$\sigma_2 = \frac{T_{\max}}{1.5\sqrt{Y_{\max}}} \quad \sigma_1 = 1.5 \quad (\text{B.47})$$

For a parabola, we may substitute  $a_2 = 0.5$  and  $a_1 = T_{\max}/\sqrt{Y_{\max}}$  into Equation B.40 and integrate this equation from zero to the water depth,  $y$ . We then obtain  $P = f(z) \times y$ , in which

$$f(z) = 2z^2 \left( \frac{1}{z} \sqrt{1 + \frac{1}{z^2}} + \ln \left( \frac{1}{z} + \sqrt{1 + \frac{1}{z^2}} \right) \right) \quad (\text{B.48})$$

where  $z$  = side slope of the furrow at the water surface.

#### Power law

FURDEV can also find the geometry parameters from a known pair of water top widths,  $T$ , and water depths,  $Y$ . These measured values of  $(Y_1, T_1)$  and  $(Y_2, T_2)$  can be entered in the geometry input window. The values of  $\sigma_1$  and  $\sigma_2$  are calculated according to Equation B.39, entering the values of  $a_1$  and  $a_2$ . These can easily be found from taking the logarithms of Equation B.37 for both input pairs.

The values of  $\tau_1$  and  $\tau_2$  are found from the wet perimeter using the same pairs of input data  $(Y_1, T_1)$  and  $(Y_2, T_2)$ . To this end, Equation B.40 is numerically integrated using the composite Simpson rule for the two values of  $Y$ . The Simpson rule says that for  $n$  pieces  $\Delta Y$  (FURDEV uses  $n = 100$ ) we can find the wet perimeter from

$$P = \frac{2}{3} \Delta Y \{f(0) + 4f(y_1) + 2f(y_2) + 4f(y_3) + \dots + 4f(y_{n-1}) + f(Y)\} \quad (\text{B.49})$$

The procedure for geometry parameters,  $\tau_1$  and  $\tau_2$ , is thus:

1. Calculate  $P_1 = f(Y_1, T_1)$  and  $P_2 = f(Y_2, T_2)$  using Equation B.49;
2. Using the known  $Y$ 's and calculated  $P$ 's, find the expressions for  $\tau_1$  and  $\tau_2$ , similar to Equations B.45 and B.46

$$\tau_1 = \frac{P_1}{Y_1^{\tau_2}} = \frac{P_2}{Y_2^{\tau_2}} \quad (\text{B.50})$$

$$\tau_2 = \frac{\log \frac{P_1}{P_2}}{\log \frac{Y_1}{Y_2}} \quad (\text{B.51})$$

## B6 Optimisation procedure for the application efficiency

The method of the golden sections has been implemented in FURDEV and BORDEV to search for the maximum application efficiency,  $E_a$ , as a function of the inflow rate,  $Q_0$  or  $q_0$  (Mode 1) or the field length,  $L$  (Mode 2). The golden section method is a powerful, one-dimensional, numerical line search method for finding a local maximum or minimum. It is more robust and reliable than interpolation-based methods, though not as efficient (McCormick 1983, Reklaitis et al. 1983). The technique searches (in this case) for the maximum by narrowing the search interval progressively in a number of iterations until the interval becomes sufficiently small. We will discuss the interval bounding and refinement algorithm in the following section, but first some of the basic features of the golden section method will be defined.

The problem to be solved can be posed as: find the maximum value of the function  $E_a = f(x)$  in a known interval of  $x$ , or

$$\text{Max } E_a \quad x \in S = [x^l, x^u] \quad (\text{B.52})$$

where

$x$  = decision variable which could be  $Q_0$  or  $L$  depending up on the calculation mode

$S$  = the search interval containing all the points between  $x^l$  and  $x^u$

$x^l$  and  $x^u$  = the lower and the upper bounds of the decision variable

At any given iteration, say at the  $m^{\text{th}}$  line search iteration, the method requires function values at four points:  $a^m < b^m < c^m < d^m$ . The method searches for the maximum by a process of interval reduction, thus  $a^{m-1} \leq a^m$  (squeezing from the left) and/or  $d^m \leq d^{m-1}$  (squeezing from the right) must always hold. Moreover, at any given iteration the placement of the interior points,  $b^m$  and  $c^m$ , is in accordance with the golden section rules, stated as

$$b^m = a^m + r_1(d^m - a^m) \text{ and } c^m = a^m + r_2(d^m - a^m) \quad (\text{B.53})$$

where  $r_1$  and  $r_2$  are the golden section constants, given as

$$r_1 = \frac{b^m - a^m}{d^m - a^m} = \frac{3 - \sqrt{5}}{2} \quad \text{and} \quad r_2 = \frac{c^m - a^m}{d^m - a^m} = \frac{\sqrt{5} - 1}{2} \quad (\text{B.54})$$

The method also assumes that the function to be minimised is uni-modal over the selected search interval, ie, that one optimum exists, to the left of which the function increases and to the right of which the function decreases. The first step is bounding the interval in which the optimum lies.

The upper bound for  $Q_0$  is the maximum non-erosive flow rate,  $Q_{\text{max}}$ .

BORDEV calculates  $Q_{\max}$  ( $\text{m}^3 \text{min}^{-1} \text{m}^{-1}$ ) using Equation B.55 (Hart et al. 1980)

$$Q_{\max} = \frac{0.01059}{S_o^{0.75}} \quad (\text{B.55})$$

FURDEV uses Equation B.56 to calculate  $Q_{\max}$

$$Q_{\max} = \left[ V_{\max} C_1 \left( \frac{n}{60 S_o^{0.5}} \right)^{C_2} \right]^{\frac{1}{1-C_2}} \quad (\text{B.56})$$

where  $V_{\max}$  = maximum non-erosive velocity ( $\text{m min}^{-1}$ ). According to Walker and Skogerboe (1987)  $V_{\max}$  ranges from  $8 \text{ m min}^{-1}$  for erodible silt to  $13 \text{ m min}^{-1}$  for more stable clay and sandy soils.

FURDEV considers the flow rate that just failed to advance to the downstream end as the minimum flow rate,  $Q_{\min}$ . This is determined as part of the optimisation process. BORDEV takes the minimum required unit flow rate as either the minimum flow rate based on advance consideration or the minimum required flow rate for adequate spread,  $Q_s$  ( $\text{m}^3 \text{min}^{-1} \text{m}^{-1}$ ), whichever is greater.  $Q_s$  is given as (Hart et al. 1980)

$$Q_s = \frac{0.000357 L \sqrt{S_o}}{n} \quad (\text{B.57})$$

If the program is run for the first time in the session in Calculation Mode 2, a value of  $L_{\text{ini}}$  is fixed internally, but if the program has been run before in another calculation mode then  $L_{\text{ini}}$  is equal to a user-specified value. This initial value of length,  $L_{\text{ini}}$ , is taken as the upper limit of the search interval, if the optimum length of the channel is less than  $L_{\text{ini}}$ . The lower limit is set such that the optimum length lies within the search interval. If, on the other hand, the optimum channel length is greater than  $L_{\text{ini}}$ , then  $L_{\text{ini}}$  marks the lower bound of the search interval and the upper limit is set such that the optimum lies within the search interval.

Now, we turn to a description of the optimisation algorithm. At any given iteration, say at the  $m^{\text{th}}$  iteration, feasibility tests and comparison of the function values at the two interior points,  $b^m$  and  $c^m$ , give rise to either of the following two cases:

1. If  $(E_a(b^m) \geq E_a(c^m))$  then  $d^m$  is dropped and  $[a^m \text{ to } c^m]$  becomes the next interval, with  $a^{m+1} = a^m$  and  $d^{m+1} = c^m$ . This is squeezing the interval from the right, because interval  $[c^m, d^m]$  disappears in the next iteration. Recall

that in addition to the interval bounds, two other interior points need to be located to execute the  $(m+1)^{\text{th}}$  iteration. One interior point,  $c^{m+1} = b^m$ , is available from the  $m^{\text{th}}$  step. The other interior point  $b^{m+1}$  can be computed in accordance with the golden section rule in Equation B.53.

2. If  $(E_a(b^m) < E_a(c^m))$  then  $a^m$  is dropped and  $[b^m \text{ to } d^m]$  becomes the new interval, with  $a^{m+1} = b^m$  and  $d^{m+1} = d^m$ . This is squeezing the interval from the left, because interval  $[a^m, b^m]$  disappears in the next iteration. One interior point  $b^{m+1} = c^m$  is available from the  $m^{\text{th}}$  step. The other interior point,  $c^{m+1}$ , can be calculated using Equation B.53.

The new interval is further refined using the function comparison and bisection procedure described above until the convergence criteria given by Equation B.58 are satisfied

$$|E_a(c^m) - E_a(b^m)| \leq \varepsilon_{fbc} \quad \text{and} \quad |c_m - b_m| \leq \varepsilon_{fc} \quad (\text{B.58})$$

where  $\varepsilon_{fbc}$  and  $\varepsilon_{bc}$  are permissible absolute deviations from zero of the respective quantities.



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