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MANAGING IRRIGATION FOR
ENVIRONMENTALLY SUSTAINABLE AGRICULTURE
IN PAKISTAN

SURFACE IRRIGATION METHODS AND PRACTICES

Assessing the Field Irrigation Performance and Alternative Management Options for Basin Surface Irrigation Systems Through Hydrodynamic Modeling

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AKNOWLEDGEMENTS

The application of a surface irrigation model is one thing. To understand the complete mathematics behind the model is a second thing. Both are required in order to apply the model successfully, along with developing a fundamental understanding of the surface and subsurface irrigation processes. For quite some time, I have been working on both of these aspects, which I like to share with those who are interested. For this purpose, I prepared this report, which discusses one of the many parts on which the Irrigation Methods and Practices team is working.

During my stay at Utah State University (USU), I had the opportunity to obtain thorough insight into the mathematical modeling, along with design and evaluation, of surface irrigation systems. The main analysis of this report has been written during my stay at USU. I would like to express my thanks to Dr. W. R. Walker, Head of the Department of Biological and Irrigation Engineering, USU. for sharing the ins and outs of SIRMOD with me and his feedback on the first draft of this report.

Additionally, words of gratitude to Dr. M.S. Shafique and Prof. G.V. Skogerboe, for their feedback concerning this report and their continuous support for my research with IIMI.

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ABSTRACT

Irrigated agriculture has always been dependent on the consgrvation of natural water resources through storage dams for surface water use, and pumping for ground water use. Countries with a semi-arid and arid climate depend heavily on additional water resources for agricultural purposes. For these countries, a water conservation plan is a necessity, not only for the purpose of saving water, but also for better management of the irrigation water in order to match the crop water requirement, and, thus, to guarantee a better yield.

In Pakistan. surface irrigation is an important component of the agriculture. In fact, irrigated agriculture accounts for about 90% **of** Pakistan's agricultural output. However, difficulties are faced in Pakistan due to limitations in canal capacity, lack of water resources, and increasing cropping intensities. Further, the excessive exploitation of ground water for irrigation purposes has a negative impact on both agriculture and the environment.

Within the Pakistan National Program of the International Irrigation Management Institute (IIMI), research is conducted on Surface Irrigation Methods and Practices. This research has as a main objective to develop sustainable improved irrigation management practices at the field and farm level in order to enhance a more efficient use of the irrigation water and to increase the crop production.

This report assesses the field irrigation performance in terms of application and requirement efficiencies and distribution uniformity, along with the impact **of** improved management options for basin irrigation systems, based on the use of surface irrigation simulation software (SIRMOD). For this study, fields have been selected at different farms, which were monitored during the Kharif 1995 and Rabi 1995 – 1996 irrigation season.

The hydrodynamic model, which solves the complete form of the Saint-Venant Equations, has been applied for the irrigation simulations. Further, the hydrodynamic model – as used in SIRMOD – is based on the Eularian integration approach. The Newton-Raphson procedure is applied for solving the equations for each computational node, and the Preissmann double-sweep algorithm is applied for solving the banded matrix, which results from the Newton-Raphson procedure.

In order to run the hydrodynamic model, the infiltration function (Modified Kostiakov-Lewis Equation) has **to** be calibrated first. In this study, the volume balance analysis has been applied in order to calibrate the infiltration functions for the selected irrigation events of four sample fields (i.e. basins).

The simulated irrigation performance assessment reveals that for two-third of the monitored irrigation events, the irrigation turns out to be either insufficient or excessive. In two instances, only a balanced irrigation has been assessed. The first irrigation events deal mostly with over-irrigation. Complete under-irrigation. partly or for the tail-end of the fields, mostly occurred for the later irrigation events. Furthermore, in quite a number of instances, the soil moisture

distribution turned out to be unsatisfactory. An unsatisfactory irrigation performance has implications for the crop yield, which is reflected in the collected yield data. Frequent tail-end under-irrigation led to tail-end crop yield reduction, whereas excessive use of water resulted in a yield reduction at the head **of** the field. For one farm, additional fields have been assessed, based on the prior derived infiltration functions. Overall, unsatisfactory irrigation performance occurs at the field level of the entire farm.

Model verification has been accomplished by comparing the simulated advance phase with the monitored advance phase. Results **show** that the advance phase is satisfactory simulated; however, some difference between monitored and predicted advance does occur. This is mostly related to the irregular tendency of the advance front, which is difficult to simulate, since the model simulates per unit width only.

The discharge - application efficiency relationship has been derived through simulation. The results reveal that the application efficiency increases by increasing the discharge. Additionally, it has been proven through the simulations that by increasing the discharge the advance time reduces. These two phenomena are of importance when its comes to improving the irrigation practices. Two scenarios have been tested: (i) impact of modifying the cutoff time on the irrigation performance; and (ii) impact of modifying the applied discharge and the cutoff time on the irrigation performance. In the over-irrigation cases, water savings could be achieved by modifying the cutoff time, whereas in the under-irrigation cases, some application efficiency has to be sacrificed in order to obtain requirement efficiency of 100%. Modifying the applied discharge, as well as the cutoff time, leads to a much better irrigation performance and the overall water savings are considerable.

The hydrodynamic model has proven to be a powerful tool for assessing the field irrigation performance, but, moreover, to develop improved irrigation practices scenarios. Through the simulations, the impact of optimizing the field irrigation performance has been quantified, which shows that for quite some irrigation events the impact is considerable in terms of water savings.

However, for the farmer it is difficult, **to** know how much water to apply in order to meet the exact crop water requirement. Further research is being conducted on basin, as well as bed - and - furrow irrigation systems in order Io address feasible operation and management techniques for the farmers in order **to** improve their field and farm irrigation performance and achieve both water savings and higher crop yields.

Keywords: Surface irrigation, basin irrigation, hydrodynamic modeling, surface irrigation simulation, irrigation performance, irrigation practices, volume balance analysis, Pakistan.

CHAPTER I INTRODUCTION

WATER AS A CONCERN FOR ALL

Conservation plans for making use of rainwater, as well as melting snow water coming from the mountains, has always been an important component for generating and conserving natural water resources through storage dams for water use purposes. Irrigated agriculture has always been dependent on this type of water source, next to ground water use for irrigation purposes. However, over the past many years, the load on the natural resources has been tremendously increased on a world-wide scale due to the increase in population, resulting in an increase in demand for food and fiber supply, and an increasing competition between agriculture, industry and domestic water **use.**

Sometime back, there was an article in a Dutch newspaper about an investigation on domestic water use in the Netherlands in terms of the average daily amount of water used by one person. Results revealed that on an average, the inhabitants of Amsterdam consume more water per day as compared to other regions in the country. When water meters were installed in the country, it was decided that for Amsterdam, instead of installing water meters, a fixed price was asked from the inhabitants of the city to cover the water expenditures. This was done, because the densely complicated house constructions made it difficult and more costly to install meters. ***So,*** the fee paid for water use is independent from the actual water use, which resulted in excessive **use** of the water in Amsterdam.

The luck with the Netherlands is that the water is sufficient and that the agriculture is not dependent on additional water supply; moreover, the drainage is of more importance rather than irrigation. This is in contradiction with many other countries, which have a semi-arid to arid climate and where agriculture cannot exist without irrigation. In this case, additional water resources are excessively used and conflicts arise due to water scarcity and an unequal water use.

Another side of the medal is that the water use highly affects the crop production. Either too much or too little water can harm the crop, and thus, a proper management of the water is a necessity in order to match the crop water requirement.

In Pakistan, surface irrigation is an important component of the agriculture, especially in arid and semi-arid areas of the lower plains (Punjab and Sindh) and areas in Balochistan. Basically, Pakistan has one of the biggest irrigation systems in the world, built by the English, and largely extended ever since the Independence in 1947. The irrigated agriculture accounts for about **90% of** Pakistan's agricultural output, and Pakistan's economy heavily depends on its agriculture.

However, Pakistan faces tremendous difficulties with managing the irrigation water, due to the limited capacity of the canal system, lack of water resources, and increasing cropping intensities. The load on agriculture and, thus, also on the water resources, has increased over the past many years due to the increase in population. The excessive exploitation of ground water for irrigation purposes has a negative impact on the agriculture and environment. Because of lowering the water table and adding salts to the aquifer, the groundwater became of poor quality, affecting the agricultural production. In Balochistan, karezes have dried out, because of the lowering of the ground water table due *to* the increase in private tubewell water use. The situation is alarming, and if interventions do not take place, Pakistan's agriculture will deteriorate in the near future.

Although, improving water use efficiency is a global concern, the related problems are diversified and cannot be generalized; thus, one single solution is not sufficient. For this reason, micro level difficulties should be investigated and problems solved at this level. Only then, can global improvements be achieved.

In Pakistan, the potential for more efficient use of the irrigation water is there at the field and farm level. By improving Ihe operation and management of the irrigation water by the farmers, not only water can be saved, by reducing the seepage losses, but also a better production can be achieved by improving the irrigation management practices and related practices. Further. by reducing the tubewell water use by proposing best management practices for on-farm irrigation practices. the salinity hazard can be reduced, leading to a more sustainable agriculture.

IRRIGATION METHODS AND PRACTICES RESEARCH

The International Irrigation Management Institute (IIMI) included under the Netherlands Government Grant Project ***"Managing Irrigation for an Environmentally Sustainable Agriculture in Pakistan",*** a research program on Surface Irrigation Methods and Practices.

This research deals with:

- Evaluating the current irrigation practices and traditionally used irrigation methods for designing improved operation and management strategies for basin irrigation systems.
- Improved surface irrigation methods, such as the furrow and bed–and-furrow irrigation methods, which have considerable advantages above the traditional basin irrigation methods. related to water use, operational and management flexibility, yield and physical related factors.
- Furthermore, under this research activity, research is being carried out on surface irrigation scheduling; conjunctive use of surface and saline-sodic ground water with amendments; and flow measurement devices for measuring farm deliveries.

Overall, the main objective can be formulated as:

Developing sustainable improved irrigation management practices at the field and farm level in order to enhance a more efficient use of the irrigation water and to increase the crop production.

Although IIMI's research on this topic is confined to Pakistan, it has not only potential for nalional impact but also for global impact, since the improved surface irrigation practices are considered as highly transferable to other irrigated areas in the world.

THE RESEARCH

Objective and goals

This report discusses the results of the research, conducted in 1995 and 1996, on the evaluation of selected basin irrigation systems in terms of performance and alternative management options.

The main objective of this research is:

Assessing the field irrigation performance in terms of application efficiency, storage efficiency and distribution uniformity, along with assessing the impact of improved management options for basin irrigation systems, based on the use of surface irrigation simulation software (SIRMOD).

Specific goals include:

- Assessing the current field irrigation performance for selected irrigation events on different fields;
- Developing management options to improve (i.e. optimize) the irrigation efficiency for the selected fields; and
- Integrated with the study, testing the application of surface irrigation simulation technology for basins.

Research site and sample farms

This research study has been undertaken in two research sites:

(1) In the Fordwah-Eastern Sadiqia Irrigation system, which has two main canals (Fordwah and Eastern Sadiqua) taking *off* from the left bank of the Suleimanki Headworks. located on the Sutlej River. Fordwah Canal bifurcates into Fordwah Branch Canal and MacLeod Ganj Branch Canal (Mahmood. 1996). Each branch has many distributaries allocating

the water among the *moghas* or outlets to the tertiary watercourse channels. IIMI's research site with respect to Surface Irrigation Methods and Practices is confined to selected watercourse command areas of two out of three tail distributaries of the Fordwah Branch Canal, i.e. Fordwah and Azim Distributaries. It concerns W/C Fordwah 14-R and WIC Azim 111-L.

(2) In Bahisti Distributary command area. This is a tail distribuary of the Chet Dawin Canal, which in turn takes off from the Malsi Canal (at Head Cher Chan). This latter canal deriviates from the Link Canal or Thangi Canal, which takes off from the left side of Ravi River at Head Sadhnai, and links with the Sutletj River.

In the Fordwah-Eastern Saddiqia Irrigation System, two farms (i and ii) have been selected for this research, while one farm has been selected from the Bahishti Distributary area (iii):

i. Yasin Farm, located in W/C Fordwah 14-R

Mr. Yasin is the tenant of this farm and has about 12.5 acres of land. According to the warabandi, he receives water every Thursday from the watercourse between 12.46 p.m. - 16.53 p.m. (for the year 1996). However, during Rabi 1995 - 1996, partly due to the yearly canal closure in January and February, he relied more on water from the tubewell at the farm. Figure 1.1 presents the map of the Yasin farm. The landholding is divided into more than 50 small bunded units, on which, during Rabi 1995 – 1996 season, mostly wheat was cultivated. Some bunded units were cultivated with fodder crop or vegetables. At Yasin Farm, two fields were selected for detailed computer irrigation simulation purpose. Field 1 (58.4 m by 17.5 m) is a fine sandy loam soil, classified as Haroonabad fine sandy loam. Field 2 **(60.25** by **14.3** m.) is a **silt** loam soil, classified as Bagh loam[1]. Both, on Field 1 and Field 2, wheat has been cultivated during the monitoring season Rabi 1995 – 1996.

ii. Nawaz Farm, located in W/C Azim 111-L

Mr. Nawaz is a lessee of the land of his neighbor and has about 6 acres of land. He entirely relies on tubewell water, in which he has a ***50%*** share. Mostly, he uses the tubewell whenever the owner does not irrigate. Basically, all of the farmers in the tail area of Azim Distributary rely on tubewell water, since hardly any water reaches the tail reach of Azim Distributary. There is no meaningful warabandi.

Furthermore, Azim Distributary is a non-perennial canal and receives water only during the kharif irrigation season. However, quite often, during the rabi irrigation season, Azim Distributary receives water whenever there is an excess of water in the Fordwah Branch, which has to be drained off.

[1] **Based on the soil classification made by Soil Survey of Pakistan, Lahore**

Figure 1.2 gives an overview of the Nawaz Farm. The landholding is divided into bunded units, varying between half of an acie to one acre in size. Most of the fields were cultivated with wheat; however, some fields were used for fodder or vegetables during Rabi 1995 – 1996. Field 3 - cultivated with wheat crop - has been selected for the computer irrigation simulation exercise. Field 3 (71.35 by 62.05 m.) is a loam soil with alkali crust, classified as Nabipur loam.

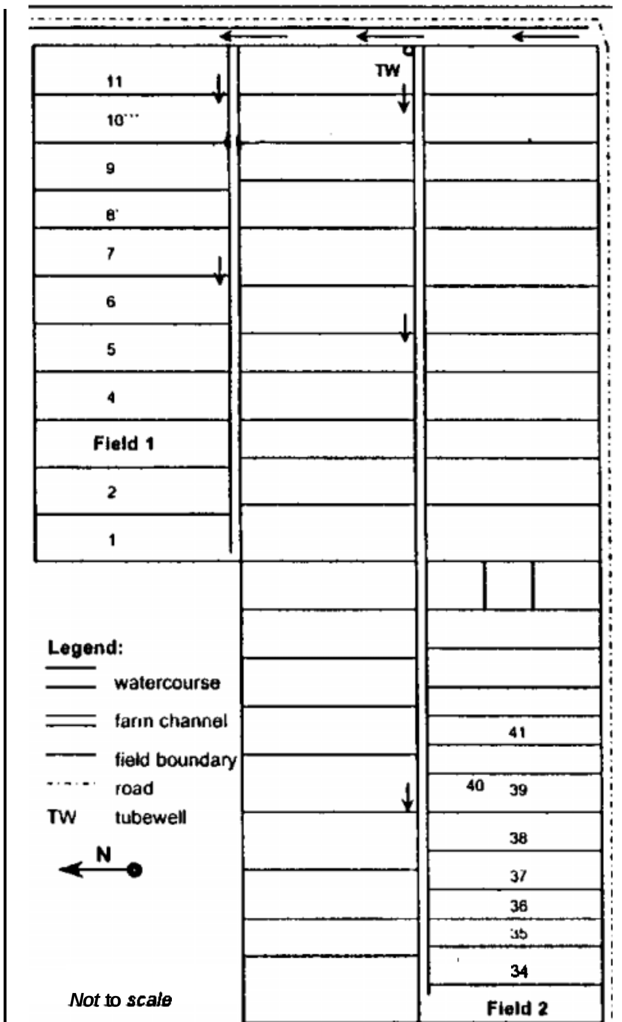


Figure 1.1. Layout **of the Yasin Farm, W/C Fordwah 14-R.**

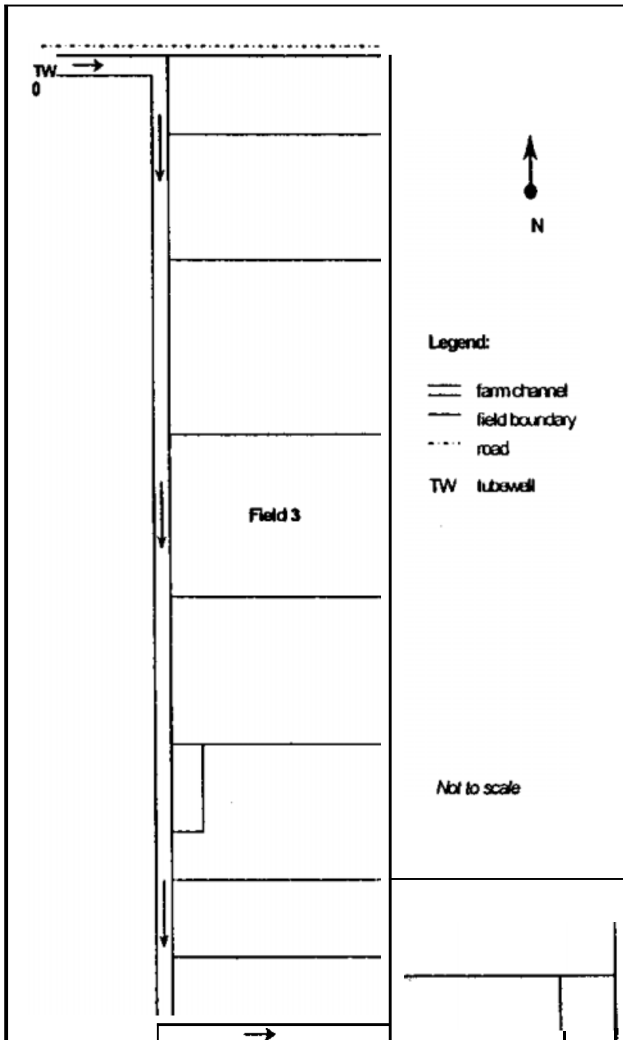
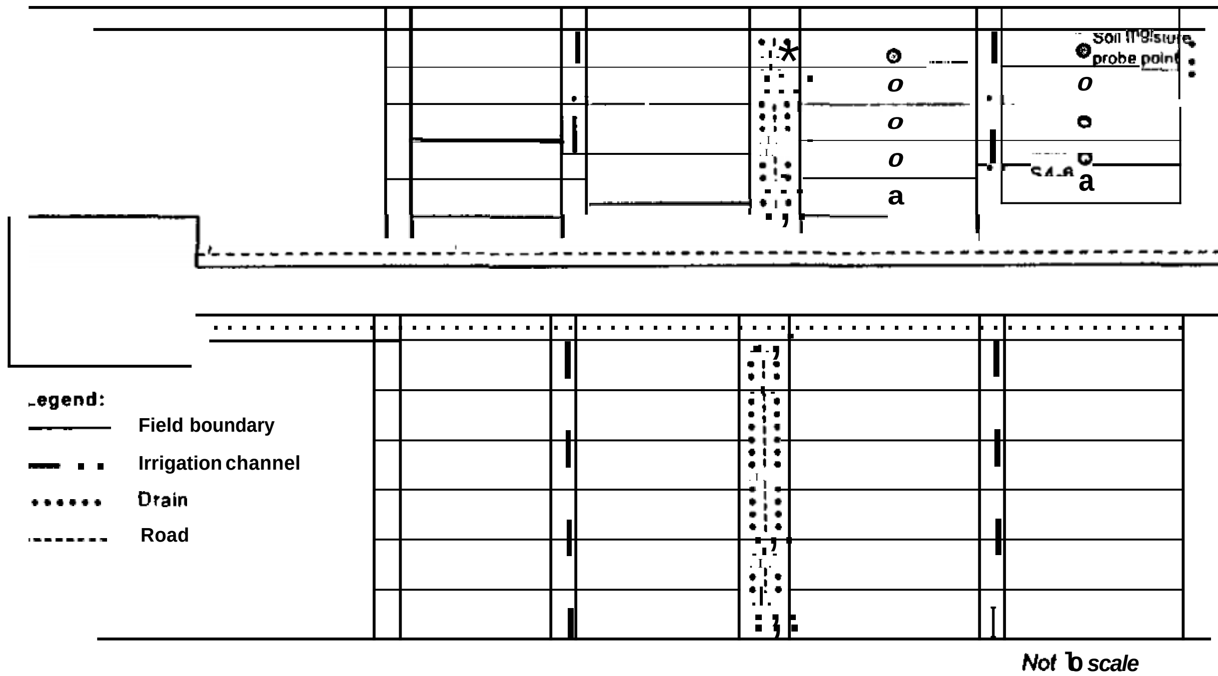


Figure 1.2. Layout of the Nawaz Farm, W/C Azim 111-L.

iii. Tareen Farm, located in Bahisti Distributary area

This is a private farm of roughly 1000 acres, located on the Multan road, near Lodhran (District Bahawalpur). Mr. Tareen is the owner of the farm, however, he has hired a manager to look after the farm. The area is served by five watercourses, which obtain water from the same canal. Three of the five watercourses are exclusive, while two out of the five watercourses are shared. The farm has a continuous water supply **(Kalwij, 1996).** The main cultivation season is the kharif season, while during the rabi season the focus is more on the orchards. During the kharif season, cotton is the predominant crop. Figure 1.3 presents a part of the farm holding. Basically. this part is used for a Cotton Agronomy Research Project[2]. Field **S4-6** has been selected for the computer simulation exercise. Field **S4-6** is a basin (147.8 m by **59.44** m), used for the cultivation of cotton. The computer irrigation simulations are based on the data collected during the Kharif **1995** season. The soil is classified as being loam – silt loam soil. At Tareen Farm, the laser leveling technique is used to level the fields. Further, the Neutron Probe is used for determining the soil-plan!-water relationship (*i.e.* volumetric soil moisture content).



igure 1.3. **Layout of part of the Tareen Farm, Chak no. 15, Lodhran.**

SIRMOD

This research relies for its analysis on SIRMOD (Surface Irrigation Simulation Model), which is a computer program, written in C language, that simulates the subsurface and surface irrigation processes and evaluates the irrigation performance for the simulated irrigation events. SIRMOD

[2] In collaboration with Hoechst Company (now called Agrevo), a chemical and fertilizer private transnational company. This joint project is on a fifty-fifty share basis between Mr. Tareen and Agrevo. The project is scheduled for the period

was developed at the Department of Biological and Irrigation Engineering, Utah State University, USA. It is a comprehensive model, dealing with the subsurface and surface irrigation hydraulics, which involves a numerical solution of the equations of continuity and momentum (Saint-Venant Equations). Three mathematical approaches for solving these equations are integrated in SIRMOD:

(i) The Full Hydrodynamic Model, which uses the complete form of the Saint-Venant Equations;

(ii) The Zero-Inertia Model, which deals with a simplification of the Saint-Venant Equations by assuming that the inertial and acceleration terms in the momentum equation are negligible for the surface irrigation conditions; and

(iii) The Kinematic-Wave Model, which deals with a further simplification of the momentum equation, and ignores. next to the inertial and acceleration terms, the Froude number. Operating Ihe Kinemalic-Wave Model is limited to open end irriqation systems and sloped fields.

In this research, the full hydrodynamic model has been used. Chapter II provides the theoretical aspects of the model.

SIRMOD provides the option for simulating furrow, basin and border irrigation systems, for open or closed end boundary conditions. Additionally, it simulates and tests different flow regimes, such as continuous flow with cutback and surge flow. Figure 1.4 presents an example of the simulation process as visually presented in SIRMOD.

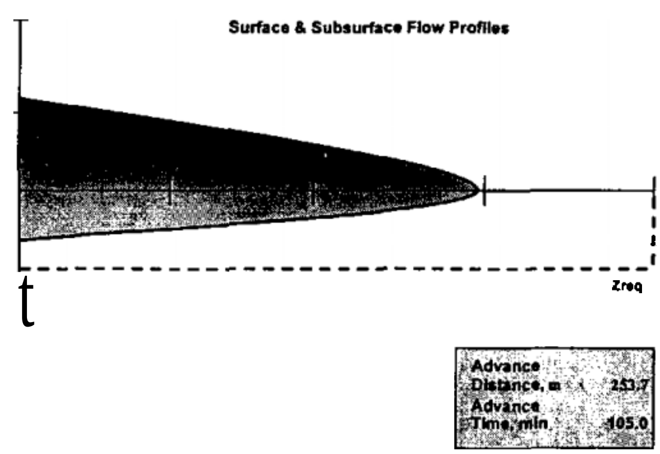


Figure 1.4. Real–time run screen of the simulation process (after Walker, 1993).

SIRMOD is a powerful tool for assessing the field irrigation performance. but foremost, it has the flexibility to test different management scenarios by changing the design variables. It is used for on-going research at the Department of Biological and Irrigation Engineering, and is widely used by different research institutes. An investigation, which concerned a comparison of four empirical based surface Irrlgatlon simulation models on accuracy in terms of predicting the advance and recession phases and runoff, and was done by Australian scientists, revealed that SIRMOD's zero-inertia model and hydrodynamic model performed the best (Zazueta, ed.. 1996).

SIRMOD requires input data, such as (i) field inlet inflow; (ii) topography; (iii) flow cross-section; (iv) irrigation duration; (v) downstream boundary condition; (vi) flow regime; (vii) calibrated Modified Kostiakov-Lewis infiltration function and (viii) the target depth of application at the end of the field.

Next to the real-time simulation of the subsurface and surface water flow and tailwater hydrograph (when the boundary condition permits), SIRMOD provides detailed output on: (i) irrigation performance assessment in terms of application and storage efficiencies and distribution uniformity; (ii) advance trajectory; (iii) recession trajectory; (iv) infiltrated water depth profle; and (v) volume balance in terms of total volume of water applied, infiltrated and run-off.

With respect to discharge, target application depth and the infiltration function, these parameters are based on field data, collected for selected irrigation evonls. The analysis of the field data concerning the discharge, advance, infiltration and soil moisture behavior are presented in Kalwij (1996) for Field S4-6 and in Kalwij (1997) for the Fields 1, 2 and 3. This research builds on these results, however, certain modifications were made. In this research, the volume balance analysis is adopted for calibrating the infiltration function, which is described in detail in Chapter III.

REPORT OUTLINE

The following sections will be presented:

- Chapter II: Surface irrigation simulation (development of the surface irrigation modelling, hydrodynamics of the water flow and basin irrigation simulation);
- Chapter III: Calibration of the infiltration function through Volume Balance Analysis (concept, analysis and results concerning the calibration of the infiltration function);
- Chapter IV: Field irrigation performance assessment in terms of application and requirement efficiencies and distribution uniformity for the selected irrigation events on different fields, and extrapolation of performance assessment to the farm level;
- Chapter V: Optimisation and management options, such as maximising the irrigation efficiency through modifying the design variables (discharge and cutoff time), and implications of improved practices on the total volume of water applied; and
- Conclusions in Chapter VI.

CHAPTER II SURFACE IRRIGATION SIMULATION

DEVELOPMENT OF SURFACE IRRIGATION MODELING

When it comes to describing the water flow, many complexities arise due to its physical characteristics: it is an unsteady *flow,* or a non-permanent. non-stationary or time-variable free-surface water flow (Yevjevich, 1975). The mathematical treatment of unsteady open-channel flow is an important but relatively difficult problem. Basically, the difficulty exists because many variables enter into the functional relalionsttip arid because the differential equations cannot be integrated in closed forms exccpl under very simplified condilions (Ycvjevich, 1975).

Already more than 170 years ago, major contributors to science, such as Laplace and Lagrange, were studying the phenomenon of unsteady flow and how to mathematically describe this. However, it was Barré de Saint Venant who, during the second half of the eighteenth century, was able to develop two partial differential equations, representing unsteady flow in open channels, which formed the backbone of further development in mathematical descriptions and treatments of unsteady flow ever since.

With entering the new era of computers, along with on-going further advancement in developing solution schemes for treating the surface irrigation water flow, it became possible to develop frameworks (i.e. models) which provide quick information on operation and management aspects of the irrigation water. Since the late fifties, a number of models have been developed dealing with the advance of the water flow for border irrigation, based on the full hydrodynamic equation, using finite difference and finite element methods. Strelkoff (1970) is considered as a main contributor to this development. Wilke (1968) applied the full hydrodynamic model for furrows and applied the method of characteristics to change the governing partial differential equations into ordinary differential equations and then use the finite difference technique (from Shafique, 1984). Bassett (1973) presented a border irrigation hydrodynamic model for the whole irrigation process (from Haie. 1984). Katapodes and Strelkoff (1977a) proposed a complete hydrodynamic model of border irrigation, using the method of characteristics on a rectangular moving-grid to solve the governing equations (from Souza, 1981). Souza (1981) solved the motion equations using the deformable control volume or integral approach of Strelkoff and Katapodes (1977) for hydrodynamic modeling of furrow irrigation. Walker and Skogerboe (1983) also solved the hydrodynamic model for furrow irrigation by using the Eularian grid system (from Shafique, 1984). Haie (1984) developed a hydrodynamic model for continous and surge surface flow, based on the Eularian integration.

A major breakthrough was achieved by Theodor Strelkoff and Nikolaos Katapodes (1977) on developing the first operational zero-inertia model of the complete irrigation process for border irrigation. Volume-integrated and time-integrated forms of the governing equations are employed in a fully implicit numerical scheme of solution (Jensen. 1983). An oblique computational grid has been applied during the advance phase, followed by a mix of oblique and rectangular grids if cutoff occurs before the water reaches the end of the border; and a rectangular grid for the time steps after the end of the advance time. The numerical solutions are more simple (as compared to hydrodynamics) and – at that time important – less expensive, based on computer costs for running the model (Shafique, 1984).

Hereafter, many researchers have continued this zero-inertia development. As mentioned in Walker and Skogerboe (1987), Clemmens and Fangmeier (1978) improved the numerical solution associated with a dyked-end condition. Clemmens (1979). Elliott et. al. (1982) and Oweis (1983) applied the zero-inertia model to the surface-irrigated conditions, including furrows. Shafque (1984) applied the zero-inertia model on leveled basin-furrows.

Several main contributors have been addressed in order to illustrate the development of computer simulation modeling of the subsurface and surface irrigation process. On a world-wide scale, researchers have been, and still are, working on surface irrigation simulation modeling, based on hydrodynamic, zero-inertia or kinematic-wave assumptions, which will undoubtedly contribute to further new developments in the field of surface irrigation.

In the following section, the hydrodynamic model, based on the Eularian integration as used in SIRMOD, is discussed in more detail.

HYDRODYNAMICS OF THE WATER FLOW

Irrigation is a complex process, segregated into different phases (i.e. advance, ponding. depletion, and recession). It requires a precise interpretation of the hydraulic conditions for each of the phases when it comes to the mathematical description of the whole irrigation process. The fundamentals of flowing water across a porous soil surface are interpreted by its continuity and its momentum. This can be considered as a one-dimensional process in which the irrigation is considered as an ***unsteady gradually varied and spatially varied flow.*** Spatially varied and unsteady refer to: (i) the discharge at a specific point changes with time due to the time-dependent intake behavior of the soil; and (ii) at the advancing end of the water body, particularly depth. also changes with time and space (Walker and Skogerboe, 1987). The term “gradually” varied implies that it is assumed that: (i) the friction slope at a section is the same as for a uniform flow having similar flow velocity; and (ii) the channel is prismatic[3] (Walker and Skogerboe. 1987).

[3] Prismatic refers to the following channel characteristics: (i) the channel is straight; (ii) the bottom of the channel has the same slope along the entire length; (iii) the cross-sectional shape of the channel is constant; and (iv) the channel roughness is the same throughout the length (lecture notes for Ph.D. surface irrigation course from Dr. M.S. Shafique).

The phenomena of continuity and momentum are described in the Saint-Venant Equations - also called the motion equations - named after A.J.C Barré de Saint-Venant, founder of these commonly used equations. In Strelkoff (1970) the equations of motion are described in their complete form, which are as follows (quoted from Strelkoff, 1970):

$$A\frac{\partial V}{\partial x}+VT\frac{\partial y}{\partial x}+T\frac{\partial y}{\partial t}+VA_x^y+q=0 \tag{2.1}$$

$$\frac{1}{g}\frac{\partial V}{\partial t}+\frac{V}{g}\frac{\partial V}{\partial x}+\frac{\partial y}{\partial x}=S_0-S_f+D_l \tag{2.2}$$

$$\text{in which } S_f=\frac{V|V|}{C^2 R}=\frac{Q|Q|}{K^2} \tag{2.3}$$

and $D_l = 0$ (bulk lateral flow) (2.4a)

$D_l = \dfrac{Vq}{2Ag}$ (seepage outflow) (2.4b)

$D_l = \dfrac{V-u_l}{Ag}q$ (lateral outflow) (2.4c)

Where: $A[x,y(x,t)]$ = cross-sectional area of flow; x = distance along the channel; y = depth of flow normal to the bottom; t = time; $V = Q/A$ = the average velocity of flow, considered positive when flow occurs in the nominally downstream direction; Q = the discharge across a section, signed in conformity with V; T = the top width of flow in a section; $A_x^y = \partial A(x,y)/\partial x$ represents the departure of the bed from a prismatic form; q = the lateral outflow ($q < 0$ for inflow) per unit length of channel; S_f = resistance slope given by Equation 2.3, in which C = the Chezy C and R = hydraulic radius; $K = AC\sqrt{R}$ = Bakhmeteff's "conveyance"; and D_l = the dynamic contribution of the lateral discharge given by Equation 2.4a, b and c; and u_l = the x-component of the inflow-velocity vector.

These complete equations of open-channel flow form the backbone of the hydrodynamics of the flowing water. These equations are first order non-linear partial differential equations, without a known closed-form solution. For solving these equations a numerical procedure is required. In this section, the Eularian integration approach is discussed (as used in SIRMOD), which is a numerical approximation of the motion equations, based on the concept of a deforming control volume comprised of individual deforming cells (Walker and Skogerboe, 1987). The volume of water in surface and subsurface storage at any time during advance is represented by an expanding control volume consisting of deforming cells (Walker and Skogerboe, 1987). In the Eularian system. three different kind of cells comprise the control volume: (i) Eularian tip cell; (ii) Eularian penultimate; and (iii) Eularian intermediate cell.

Basically, the Eularian integration approach indicates that the principal deformation occurs at the downstream boundary and the cells are stationary (i.e. use of Lagrangian computational grid system). Conceptually, the approach considers the surface and subsurface water profile along the wetted portion of the field during sequential time steps (Walker and Skogerboe. 1987). During each time step, the flow advances an incremental distance, keeping a fixed time increment. The irrigation process can be graphically presented by a two dimensional time - distance grid system, consisting of rectangular and triangular cells, representing the first and intermediate cells, thnn thn lip colls, rospoctivoly (Figuro 2.1).

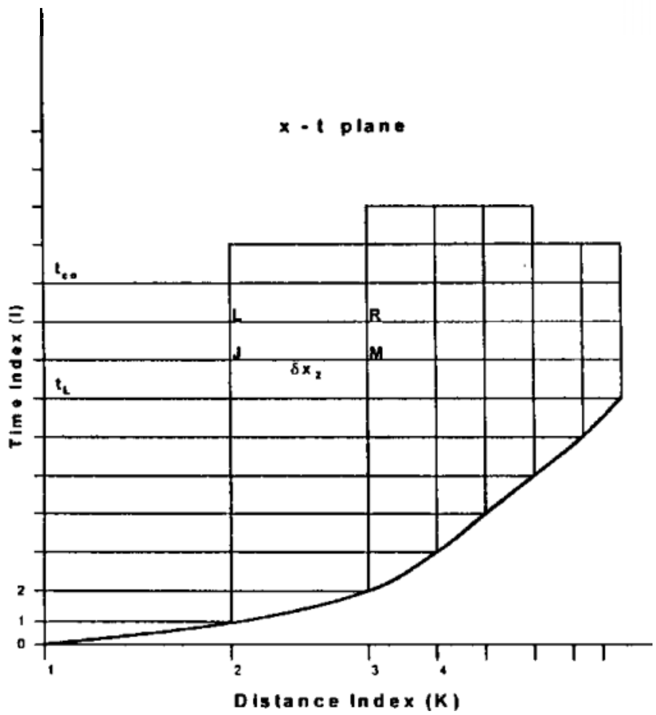
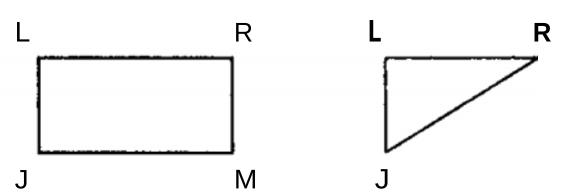


Figure 2.1 Two dimensional time - distance grid system (after Haie, 1984) .

In fact, the grid system is a network of points in the distance-time plane, whereby the region of interest within the plane is bounded in distance by left and right, or upstream and downstream, boundaries. The region is bounded in time only at the instant the solution begins. After this initial condition, the solution advances through time between the designated spatial boundaries (Haie, 1984). The upstream and downstream computational boundaries are usually physically related to the field conditions. The integral approach linearizes the motion equations, which are described for each cell as in the time - distance grid system and have to be solved for each cell. Figure 2.2 presents the details of the two types of



Rectangular cell, Triangular 'tip' cell

Figure 2.2 Schematic presentation of a rectangular and triangular "tip" cell (after Walker and Skogerboe, 1987).

Symbol L presents the condition (i.e. discharge Q, cross sectional area A and infiltrated water depth Z) at time *'t'* at the left boundary of the cell; R presents the condition at time *'t'* at the right boundary of the cell; J presents the condition at time '$t_{(i\ 1)}$' at the left boundary of the cell; and M presents the condition at time '$t_{(i\ 1)}$' at the right boundary of the cell.

The hydrodynamic model consists of two non-linear governing equations in the two unknowns Q and A at a particular x and t (Haie, 1984). Z is calculated through the derived empirical infiltration relationship (i.e. Kostiakov Lewis Equation) and is known for each time step. With this, it is assumed that the infiltration is a unique function of opportunity time, and therefore, these variables are known at all nodes and at both times (Walker and Skogerboe, 1987).

For each L, R, J and M node of each cell, the motion equations have to be solved, i. e. the values of the L, R, J and M sub-scripted physical parameters are calculated.

The complete finite approximation of the motion equations, as written for each node, is for the continuity and momentum equation. respectively (after Walker and Skogerboe, 1987):

$$[\theta(Q_L - Q_R) + (1-\theta)(Q_J - Q_M)]\delta t - [\phi(A_L + Z_L - A_J - Z_J) + \qquad (2.5)$$

$$(I - \phi)(A_R + Z_R - A, \ - Z_M)]\delta x = 0$$

$$\frac{1}{g}\frac{[\phi(Q_L - Q_J) + (1-\phi)(Q_R - Q_M)]}{\delta t} + \frac{\theta[(P + Q^2/Ag)_R - (P + Q^2/Ag)_L]}{\delta x} + \qquad (2.6)$$

$$\frac{(1-\theta)[(P + Q^2/Ag)_M - (P + Q^2/Ag)_J]}{\delta x} - S_0\{\theta[\phi A_L + (1-\phi)A_R] +$$

$$(1-\theta)[\phi A_J + (1-\phi)A_M]\} + \theta[\phi D_L + (1-\phi)D_R] +$$

$$(1-\theta)[\phi D_J + (1-\phi)D_M] = 0$$

where: Q = flow across the different cell boundaries: **A** = cross sectional flow area; Z = infiltrated volume per unit length; **P** = pressure term: $P = e_1A^{e2}$. e_1 and e_2 are parameters. related to Ihe top width - depth relationship of a cross sectional area; **D** = drag, which equals S_f * **A.** with S_f as the friction slope; ϕ = time averaging coefficient; θ = space averaging coefficient; 61 = time increment; δx = distance increment; g = acceleralion term; and S_0 = field slope.

As an initial condition, the J, M, and R subscripted variables in Equation 5 and Equation 6 are zero. So, at t = 0, Q, A and Z are zero. The discharge is assumed equal to the inflow per furrow or unit width for the following times until t = t_{co}. During advance, Q and A at the right boundary are zero, but the incremental advance, δx, is unknown. The downstream boundary condition is defined by a tip cell during the advance phase, followed by a rectangular cell when the advance phase is completed. If the field is free draining, A is often expressed as a function of **Q** by assuming a uniform flow exit. If the field is dyked, as in the case of basins, ***Q*** approaches zero[4]. Hence, at nodes 1 – N-1, there are two unknowns, while only one unknown occurs at the first (0) and **last** node (N). respectively.

Summarized, Equations 2.5 and 2.6 lorm a system **of** linear equations to be solved (i.e. having 2N-2 unknowns) at all computational points for every time step Ft during the period **of** computation. In **SIRMOD.** this resulting system is solved by the Newton-Raphson iterative procedure. The implicit equations and boundary conditions are organized in a banded matrix for solving the Saint-Venant Equations. The iterative procedure requires the assignment of trial values to the unknowns (Souza, 1981). The trial values are the known values from the previous time-line (for the first time step an initial estimate is made for the values). After each iteration, a set of residuals of the continuity and momentum equations. R_c and R_m are produced by substituting the values **of** the unknowns into the system, correcting the values of the unknowns unil the residuals are within a specified tolerance level where convergence is assumed (Haie. 1984). Convergence will never be achieved when the tolerance level is set to precisely zero.

The residuals R_c and R_m are written as a Taylor Series expansion (after Walker and Skogerboe, 1987):

$$R_c^{n+1} = R_c^n + \left(\nabla R_c^n\right)\Delta R_i^n \qquad (2.7)$$

$$R_m^{n+1} = R_m^n + \left(\nabla R_m^n\right)\Delta R_i^n \qquad (2.8)$$

The superscrips refer to the iteration. **V** = the gradient term, which is elaborated in **a** matrix form; and A = the difference term.

The residuals at the improved solution (R_c^{n+1} and R_m^{n+1}) are a function of the current solution.The residuals are presented as a set **of** linear algebraic equations for each cell, resulting in a matrix structure (i.e. banded matrix), in which the first and last line correspond to the boundary condition.

The equations (i.e. the matrix) can be solved by any standard method of solution. Liggett and Cunge (1975) presented a solution procedure, called Preissmann implicit method, developed since 1960. This solution procedure is quite commonly used because of its "time-saving" aspect. which has been used in SIRMOD. The procedure, as mentioned in Ligget and Cunge (1975). is a so-called double sweep technique. This is a general name given to a recursive type **of** Gauss

[4] **In order to ensure numerical stability. the discharge *is* not set to zero at the time of cutoff for the closed end downstream boundary condition, but should be decreased towards zero in** two **time steps (Haie, *1984).***

elimination technique, and is the most efficient method of solving banded matrices. such **as** those arising in connection with implicit numerical modeling (Souza. 1981).

The double-sweep method is an elimination procedure; the evaluation begins at the upstream end and proceeds sequentially from cell to cell to the downstream end. This completes the first sweep. Beginning next with the known downstream boundary condition, the procedure then solves pairs of cell equations for the nodal corrections in the unknowns at each successive node, proceeding in the upstream direction to node one; this completes the second sweep. The number of elementary operations necessary to solve the system of equations in this way is proportional to the number of node points N (Souza, 1981).

The outcome of this procedure are the incrementals δQ, 6A and δx for each cell during the advance phase. For more conceptual details about this procedure, the reader is referred to Liggett and Cunge (1975), Souza (1981), Haie (1984). Shafique (1984) and Walker and Skogerboe (1987).

During the ponding, depletion, and recession phases, the same principle of solving the equations is used, however, the physical conditions have to be adjusted for these phases. The recession phase is a reciprocal procedure from the advance, wherein the cells consequently are eliminated. In SIRMOD, for numerical reasons, the recession time is considered to be completed when only 5% of the water remains. Further, in order to handle numerical instability (e.g. due to the large number of time steps) certain adjustments and corrections ought to be made in the whole numerical procedure of solving the equations for each node and for each time step.

BASIN IRRIGATION SIMULATION

A basin is characterized by having a field entirely dyked where no water losses due to runoff occurs. Generally, basins have a very small or zero-slope, which requires an estimation of the friction slope. Recession and depletion occur almost at the same time and nearly uniform over the entire basin. Generally, basins are not sensitive for erosion because of its zero slope, which especially counts for heavier soil types; however, some erosion may occur downstream of the field inlet due to the high water force. Due to the flat slope, the driving force on the flow is solely the hydraulic **slope** of the water surface (Walker, 1989). This makes it very important that topography is uniformly smooth across the field in order to achieve a uniform water distribution.

The principle advantages associated with level basin irrigation systems include high potential application efficiencies and uniformities, low energy and labor requirements, and simpler management requirements (Iqbal and Clyma, 1996). However, this potential can only be achieved when the crop water requirement is known, along with how long to irrigate, or how much water to apply. Furthermore. a precise leveling of the field is an asset for achieving maximum uniformity.

Because of the closed end boundary condition, maximum application efficiency implies a (reasonable) maximum unit inflow, with the water depth not exceeding the height of the field dykes or resulting in an advance rate too high at the lower end of the field. A good discharge provides a smooth regular advance phase, not resulting in high ‘tail reach’ velocities.

In simulation, it is assumed that immediately upon cessation of inflow, the water surface assumes a horizontal orientation and infiltrates vertically (Walker, 1989). Conceptually, the basin is simulated per unit width and assumes that the infiltration behavior and the roughness coefficient remain constant over the entire length of the field.

CHAPTER III CALIBRATION OF THE INFILTRATION FUNCTION THROUGH VOLUME BALANCE ANALYSIS

CONCEPT OF THE VOLUME BALANCE ANALYSIS

SIRMOD software uses a Kostiakov-Lewis relation to describe cumulative infiltration under continuous flow regimes. It is an empirical relationship, and, thus, the ascribed values cannot be directly measured from the field, but have to be calibrated prior to the performance of the irrigation simulation. For this reason, the infiltration is somehow a difficult parameter to derive and evaluate. A general practice for measuring the infiltration is the use of a static water condition by using ring infiltrometers or by ponding tests. But these techniques often fail to indicate the typically dynamic field condition (Walker, 1989). As a result, different techniques have been developed, whereby the derivation of the infiltration function is based on certain irrigation-related processes. For reference on a different technique, except as be will discussed here, the reader is referred to Shafique and Skogerboe (1987).

The Volume Balance analysis -which is used in this report to calibrate the parameters 'k' and 'a' of the Modified Kostiakov-Lewis Equation – has been proposed by Elliot and Walker (1982). In their analysis, the field representative infiltration function is based on the response of the field to an actual watering (Walker, 1989). In fact, a volume balance is performed at two points along the length of the field during the advance phase. Next to advance data, this analysis takes into account the: (i) field inlet discharge; (ii) field surface roughness; and (iii) inflow – outflow (only in the case of an open-end boundary condition). Initially, the Volume Balance analysis has been performed and verified for graded furrows only, however, later on, the same approach has been applied for borders and basins.

As described in Walker and Skogerboe (1987). the power advance solution of the volume balance analysis is based on two assumptions:

- The trajectory of the advance of the water front in a furrow or border can be described as a simple power function, with distance as the dependent parameter:

$$x = p(t_a)_x^r \tag{3.1}$$

where: x = distance (m); $(t_a)_x$ = elapsed advance time to the distance. x; and p and r are curve fitting parameters (r presents non-linearity).

This advance relationship also holds good for basin irrigation systems, however, due to the irregular tendency of the advance front in the basin, a wetted area versus time is a more appropriate relationship to use.

- The infiltration function has the Kostiakov-Lewis characteristic form:

$$Z = k\tau^{a} + f_0\tau \tag{3.2}$$

where: Z = cumulative infiltrated water volume (m^3/m); τ = intake opportunity time (min); k = Intake constant ($m^3/min^a/m$; a = intake power; and f_o = basic intake rate ($m^3/min/m$).

Equation 3.2 describes a functional relationship between the infiltrated water volume, or depth, and the intake opportunity time. It is a practical and applicable functional relationship, whereby:

- The 'k' parameter relates to the infiltration rate (and initial infiltrated water depth);
- The 'a' parameter reflects the non-linearity and relates to the exponent 'r' of Equation 3.1; and
- f_0 reflects the basic intake rate (which can be close to the hydraulic conductivity). In fact the second part at the right side of Equation 3.2 is an additional term for the asymptotic long-time infiltration rate. Depending on soil type and total irrigation time, this basic rate is often reached well before the end of a given irrigation event (Elliott and Walker, 1982).

The first term on the right side of Equation 3.2 dominates in the beginning of the infiltration process, whereas the second term on the right side of Equation 3.2 increases in its dominance with increasing time for as long as the infiltration process proceeds.

In some of the literature, the parameters k, a, and f_0 are represented by A. B and C, respectively (e.g. Elliott and Walker, 1982; Shafique and Skogerboe, 1987); however, in order to remain consistent with SIRMOD, the infiltration function as presented in Equation 3.2 is used for further analysis.

Based on the principle of mass balance and the before mentioned two assumptions, the volume balance is mathematically described as follows (Walker and Skogerboe. 1987):

$$Q_0 t = \sigma_y A_0 x + \sigma_z k t^a x + \frac{f_0 t x}{I + r} \tag{3.3}$$

where: Q_0 = inlet discharge ($m^3/min/m$); t = elapsed time (min); A_0 = cross-sectional area of the flow at the inlet (m^2); σ_y = surface storage factor; σ_z = Kiefer correction factor or subsurface shape factor; x = advance distance (m); 'k' ($m^3/m/min^a$) and 'a' are empirical parameters and f_0 reflects the basic intake rate ($m^3/m/min$) of the Modified Kostiakov-Lewis Equation.

The Kiefer correction factor represents a relationship between the exponent 'a' of the infiltration function (Equation 3.2) and the fitting parameter 'r' of the advance function (Equation 3.1). and is defined as:

$$\sigma_z = \frac{a + r(1 - a) + 1}{(1 + a)(1 + r)} \tag{3.4}$$

The cross-sectional area, A_0, is related to the hydraulic section, which is described by: (i) a wetted perimeter - area relationship; (ii) an area - hydraulic radius relationship; and (iii) an area - depth relationship[5].

Additionally, the size of A_0 is related to the inlet discharge, field roughness and field slope and can be calculated through the uniform flow equation (Walker and Skogerboe. **1987):**

$$A_0 = [(Q_0^2 n^2) / (\rho_1 3600 S_0)]^{(1/\rho_2)} \tag{3.5}$$

where: n = Manning's roughness coefficient; S_0 = field slope; and ρ_1 and ρ_2 are the constants of the area - hydraulic radius relationship: $A^2R^{4/3} = \rho_1 A^{\rho_2}$

For basin and border systems, ρ_1 is equal to 1, and ρ_2 is equal to 10/3 (reflecting the rectangular shape of the cross-sectional flow for basins and borders). As indicated earlier in Chapter II, for basins, the driving force on the flow is solely the hydraulic slope of the water surface. For this friction slope, an approximation has to be made and it is assumed that the friction slope is equal to the inlet depth, divided by the distance covered by the water, leading to "y/x". In contrast with (graded) furrow and border systems, where A_0 remains constant, for basin irrigation systems, A_0 changes continually during the advancing phase of the water flow, which should be included in the calculations.

Based on the two-point method of Elliott and Walker (1982), the volume balance is computed for two points along the field, usually to the end of the field (x = L) and to the half length of the field (x = 0.5L), respectively. A logarithmic transformation is used to linearize the volume balance equations.

The parameter 'a' is solved through the following relationship (Walker and Skogerboe, **1987):**

$$a = \frac{\ln(V_L / V_{0.5L})}{\ln(t_L / t_{0.5L})} \tag{3.6}$$

where:

$$V_L = \frac{Q_0 t_L}{L} - \sigma_y A_0 - \frac{f_0 t_L}{1 + r} \tag{3.7}$$

[5] For conceptual details on the flow cross-sectional relationships, the reader is referred to Shafique **(1984).** Walker and Skogerboe **(1987)** ,Walker **(1989).** Walker **(1993).**

and:

$$V_{0.5L} = \frac{Q_0\, t_{0.5L}}{0.5L} - \sigma_y A_{00} - \frac{f_0 t_{0.5L}}{1+r} \qquad (3.8)$$

A_{00} refers to the cross-sectional area to the half length of the field. and V_L and $V_{0.5L}$ refer to the volume of water at the end of the field (end of advance phase) and to the half length of the field, respectively. The 'k' parameter is solved through the following derived relationship:

$$k = \frac{V_L}{\sigma_z\, t_L^a} \qquad (3.9)$$

CALIBRATION OF THE INFILTRATION PARAMETERS: RESULTS

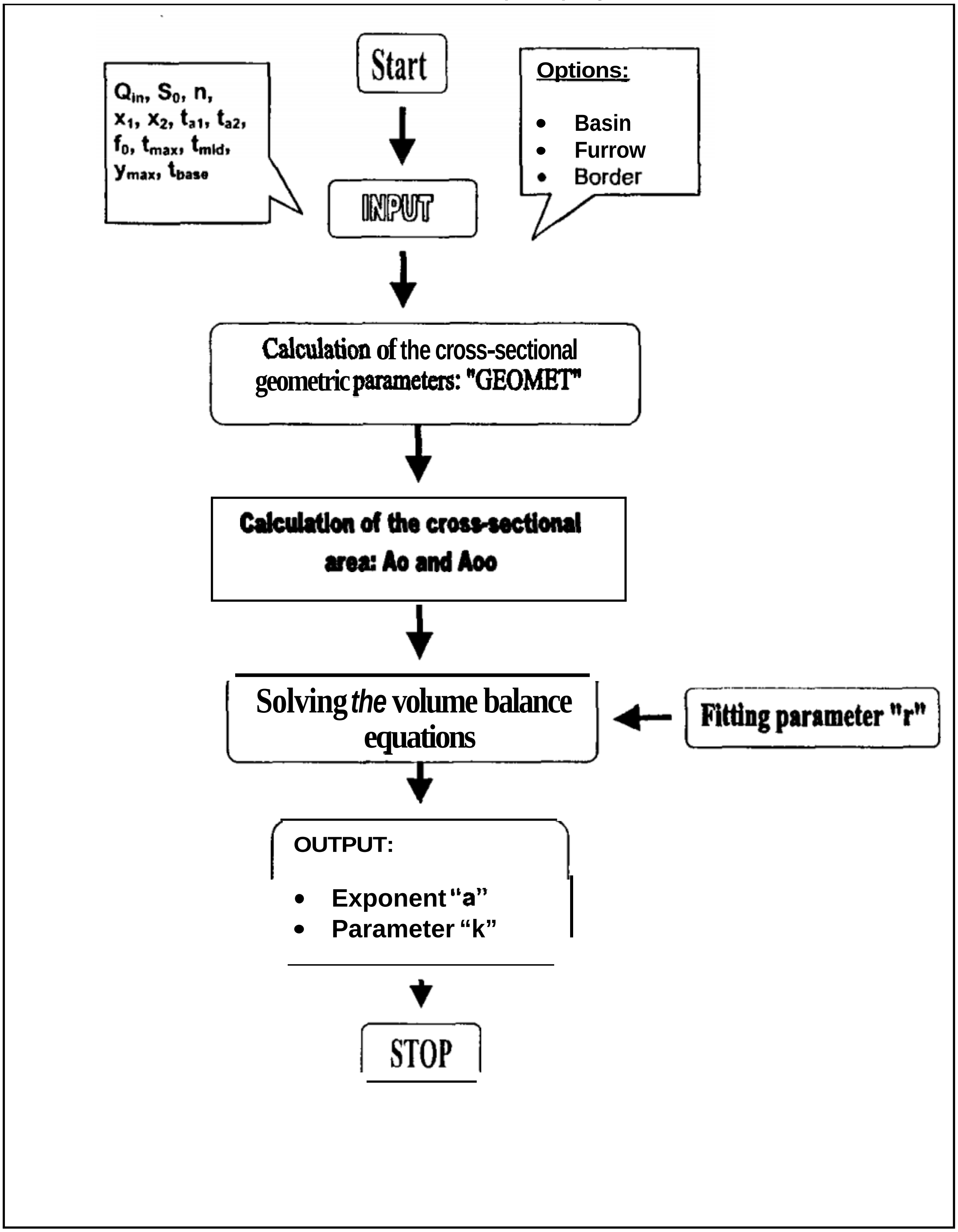
To facilitate the calibration process, a volume balance program has been written in Borland C++, based on the mathematical relationships as presented in Elliott and Walker (1982), Walker and Skogerboe (1987) and Walker (1989). The needed input data for the computer program are summarized in Table 3.1. The flow chart of the computer program, written in C++, is given in Figure 3.1.

For the Fields 1 and 2, the basic intake rate has been based on the published data as presented in FAO Paper 45 (Walker, 1989). The reason for this is that the graphical interpretation of the infiltration rale. measured through gauge readings at tho head and tail of the field, did not hold good for the different monitored irriqalion events. The basic intake rale was too difficult to derive due to the instability in the gauge readings. The reason for maintaining the field reading for Field 3 was the fact that it concerns a typical soil, with an alkali crust, and showed characteristics of very low basic infiltration rates, beyond what is published for heavy soils. For Field S4-6, the basic intake rate has been determined through infiltration test readings. Data were available[6] for Events 1 and 3. For Event 2, the basic intake rate concerns an extrapolation, based on the basic intake rate, determined for Event 1 and Event 3, respectively.

The roughness coefficient, n, cannot be measured directly in the field; therefore, a value should be ascribed - ranging between 0.02 for a smooth, just tilled surface to 0.15 for a rough and dense soil surface -, which more or less represents the usual field condition. In this context, an estimate has to be made for n, not exceeding this range. Which value to take for "n" is irrelevant in this context. The hydraulic performance is independent from "n". Further, the selection of "n"

[6] During Kharif 1995, data has not been collected for determining the infiltration rate. However. during Kharif 1996, infiltration tests were conducted at the sample fields. Since, the soil type for Field S4-6 is the same as for the field used for the infiltration test, and assuming that the infiltration rate does not differ much from season to season, it is assumed that these readings hold good for Field S4-6. For determining the basic intake rale. the infiltralion readings, collected by Mr. *T.* Iqbal (Msc student. Centre of Excellence in Water Resources Engineering, Lahore) were used for this purpose

Figure 3.1. Flow chart of infiltration calibration computer program, written in C^{++}.



is always an arbitrary choice, since during the irrigation "n" also changes (personal communication with Dr. W.R. Walker). Since Field **S4-6** has been laser leveled, the roughness coefficient is assumed to be less, ranging between 0.04 to 0.05 (i.e. the laser land leveling technology provides a much smoother soil surface, free of any major irregularities).

Table 3.1. Input data for the volume balance analysis for selected irrigation events on the Fields

	Date	Q_0 m^3/min/m	x_1 m	x_2 m	t_{a1} min	t_{a2} min	r	f_0 m^3//min/m	n
> Field S4-6									
Event 1	25/08/95	0.12019	147.83	79.76	135	48	0.5967	0.000067	0.05
Event 2	12/09/95	0.15920	147.83	55.23	75	16	0.6373	0.000054	0.04
Event 3	04/10/95	0.14528	147.83	59	50	15	0.7630	0.000047	0.05
> Field 1									
Event 1	14/01/96	0.06789	58.4	30	80	25	0.573	0.000193	0.08
Event 2	06/02/96	0.07698	58.4	30	43	15	0.633	0.000174	0.07
Event 3	29/02/96	0.06786	58.4	28.7	58	20	0.669	0.000155	0.08
Event 4	12/03/96	0.07135	58.4	29.3	46	17	0.696	0.000155	0.09
> Field 2									
Event 1	23/01/96	0.12665	60.3	28	55	15	0.590	0.000174	0.08
Event 3	29/02/96	0.11198	60.3	28	52	15	0.617	0.000136	0.08
Event 4	12/03/96	0.11056	60.3	29.3	45	15	0.657	0.000117	0.09
Event 5	28/03/96	0.22815	60.3	30	30	10	0.635	0.000117	0.09
> Field 3									
Event 1	19/01/96	0.00668	71.35	05.7	249	80	0.600	0.000022	0.08
Event 2	07/02/96	0.00593	71.35	35.7	160	50	0.530	0.00002	0.07
Event 3	02/03/96	0.00612	71.35	35.7	140	50	0.530	0.00002	0.08
Event 4	17/03/96	0.00698	71.35	35.7	77	30	0.731	0.00002	0.09

Q_0 = inlet discharge (m^3/min); x_1 (m) = advance distance to the end of the field in advance time t_{a1} (mi

?

Table 3.2 presents the results of the volume balance analysis and provides the input for SIRMOD in order to further refine the infiltration function (i.e. final calibration). When necessary, the values of k and f_0 were equally changed in order to match the simulated advance time $(t_a)_L$ with the observed advance time (i.e. resulting in a parallel shift of the graph, which can **be** either upwards or downwards).

Table 3.3 presents the calibrated infiltration functions, which are used further for the performance assessment and optimization procedure.

The volume balance approach holds good for defining the infiltration parameters for leveled field conditions. However, it is not considered to be as accurate for a zero-slope field condition as compared with graded field conditions (personal communication with Dr. W.R. Walker), because of the approximation of the friction slope for leveled field condition. The main problem faced with this approach is the sensitivity of several parameters. The fields are relatively quite small (Fields 1, 2 and 3). *so* any kind of small overestimation or underestimation in the monitoring of the advance timings have an impact on the 'r' value of the advance function, which can either become too high or too low. Further, the derived values for f_0 have major implications on the exponent 'a' of the infiltration function. An overestimation of f_0 results in negative values for the exponent 'a'.

Table **3.2.** Results of the volume balance analysis (k and a) and model Input data for **Fields S4-6, 1, 2 and 3.**

	Date	Q_0 (l/s/m)	x_f (m)	t_{co} (min)	n	k ($m^3/min^a/m$	A	f_0 ($m^3/min/m$)	Z_{req} (m)
> Field S4-6									
Event 1	25/08/95	2.0031	147.83	127	0.05	0.00658	0.5376	0.000067	0.063
Event 2	12/09/95	2.6533	147.83	72	0.04	0.00418	0.6110	0.000054	0.068
Event 3	04/10/95	2.4214	147.83	45	0.05	0.00171	0.4910	0.000047	0.066
> Field 1									
Event 1	14/01/96	1.132	58.4	90	0.08	0.00840	0.4931	0.000193	0.052
Event 2	06/02/96	1.283	58.4	44	0.07	0.00477	0.5151	0.000174	0.056
Event 3	29/02/96	1.131	58.4	61	0.08	0.00714	0.4571	0.000155	0.060
Event 4	12/03/96	1.189	58.4	46	0.09	0.00569	0.4260	0.000155	0.049
> Field 2									
Event 1	23/01/96	1.811	60.3	78	0.08	0.00781	0.5810	0.000174	0.052
Event 3	29/02/96	1.601	60.3	55	0.08	0.00681	0.5623	0.000136	0.063
Event 4	12/03/96	1.581	60.3	54	0.09	0.00587	0.5395	0.000117	0.060
Event 5	28/03/06	3263	603	29	000	0.00700	0.6340	0.000117	0.041
> Field 3									
Event 1	19/01/96	0.415	71.35	250	0.08	0.00711	0.4493	0.000022	0.077
Event 2	07/02/96	0.368	71.35	164	0.07	0.00252	0.5511	0.00002	0.069
Event 3	02/03/96	0.380	71.35	155	0.08	0.00340	0.4300	0.00002	0.055
Event 4	17/03/96	0.433	71.35	147	0.09	0.00123	0.4883	0.00002	0.061

One must not consider the derived infiltration function as a fixed relationship, but may highly vary within the field, between seasons. depending on the cultural practices, cultivation and soil surface condition. However, the derived infiltration functions can be considered as a good representation of the soil infiltration behavior as derived for different irrigation events for different fields.

The main advantage of the volume balance approach is that the roughness coefficient is included in the calibration procedure. Keeping the same roughness coefficient in the model, in some instances, a slight modification had to be made in the infiltration function to match the simulated advance time with the monitored advance time.

Table 3.3. The calibrated modified Kostiakov-Lewis infiltration function for selected irrigation events on the Fields S4-6, 1, 2 and 3.

- **Field S4-6 (Tareen Farm): silt loam – loam soil.**
  - *Evenf 1:* $Z = 0.00658\tau^{0.5376} + 0.0000671 \Rightarrow$ $Q_0 = 2.0031$ *IIslrn*
  - *Event 2:* $Z = 0.00417\tau^{0.6110} + 0.000054\tau \Rightarrow$ $Q_0 = 2.6533$ l/s/m
  - *Event 3:* $Z = 0.00171\tau^{0.4910} + 0.000047\tau \Rightarrow$ $Q_0 = 2.4214$ *IIslrn*
- **Field 1 (Yasin Farm): Fine sandy loam soil.**
  - *Event 1:* $Z = 0.00840\tau^{0.4931} + 0.0001931 \Rightarrow$ $Q_0 = 1.132$ llslm
  - *Event 2:* $Z = 0.00477\tau^{0.5151} + 0.000174 \Rightarrow$ $Q_0 = 1.283$ *IIslrn*
  - *Event 3:* $Z = 0.00714\tilde{}^{0.4571} + 0.000152\tau \Rightarrow$ $Q_0 = 1.131$ l/s/m
  - *Event 4:* $Z = 0.005691^{0.4260} + 0.000151\tau \Rightarrow$ $Q_0 = 1.189$ l/s/m
- **Field 2 (Yasin Farm): Silt loam soil.**
  - *Evenf 1:* $Z = 0.00781\tau^{0.5810} + 0.000174\tau \Rightarrow$ $Q_0 = 1.811$ *IIslrn*
  - *Evenf 3:* $Z = 0.00681\tau^{0.5623} + 0.000136 \Rightarrow$ $Q_0 = 1.601$ l/s/m
  - *Evenf 4:* $Z = 0.00587\tau^{0.5359} + 0.0001171 \Rightarrow$ $Q_0 = 1.581$ *IIslrn*
  - *Event 5:* $Z = 0.00780\tau^{0.6340} + 0.000117 \Rightarrow$ $Q_0 = 2.175$ l/s/m
- **Field 3 (Nawaz Farm): loam soil with alkali crust.**
  - *Event 1:* $Z = 0.07050\tau^{0.4493} + 0.0000161 \Rightarrow$ $Q_0 = 0.415$ llslm
  - *Event 2:* $Z = 0.00253\tau^{0.5511} + 0.000025\tau \Rightarrow$ $Q_0 = 0.368$ *IIslrn*
  - *Event 3:* $Z = 0.00390\tau^{0.4300} + 0.0000191 \Rightarrow$ $Q_0 = 0.380$ *IIslrn*
  - *Event 4:* $Z = 0.00120\tilde{}^{0.4003} + 0.000017\tau \Rightarrow$ $Q_0 = 0.433$ llslm

CHAPTER IV IRRIGATION PERFORMANCE ASSESSMENT

CONDITIONS AND PERFORMANCE INDICATORS

For the selected irrigation events on the Fields **S4-6,** 1, 2 and 3, the hydrodynamic model was used for simulating the irrigation events. As an output of the simulation, an assessment was made of the field irrigation performance for the selected irrigation events for Fields **S4-6, 1,** 2 and 3. The required input data are presented in Table 3.2. and in Table 3.3 for the infiltration parameters. Along with the input data, some assumptions and conditions were included:

- The downstream boundary condition is blocked end, and therefore no runoff occurs;
- The inflow shutoff control is by time;
- The roughness coefficient is kept at the same values for the selected irrigation events as used in the volume balance analysis; and
- The flow regime is a continuous flow without cutback or reuse.

For this research, three independent hydraulic performance indicators were used to assess the irrigation performance, which are calculated in the irrigation simulation model. The application efficiency and requirement efficiency evaluate the adequacy of an applied irrigation, while the *distribution uniformity* evaluates the soil moisture distribution. The following definitions are ascribed to lhe perlormance indicators (after Walker, 1993):

- Application efficiency, E_a (%):
  The ratio of water stored in the rootzone to the total application.
- Requirement efficiency, E_r (%):
  The ratio of rootzone storage to the total rootzone storage capacity (just prior to the irrigation event).
- Distribution uniformity, DU (%):
  The average depth of water applied in the last quarter of the field divided by the average depth applied to the entire field.

While using these performance indicators, certain assumptions have to be taken into consideration as presented in Hart et. al. (1979): (i) All the water delivered to the field edge but not absorbed through infiltration or collected as runoff for reuse is considered as loss, and the nature of this loss (i.e. evaporation, runoff, etc.) is not important; (ii) The requirement at the time of irrigation is the water required to fill the available rootzone water storage, and this requirement is equal throughout the field; and (iii) a single lumped parameter is adequate to characterize the distribution of water from an irrigation.

RESULTS OF THE SIMULATIONS

Table **4.1** presents the results of the model simulations for the selected irrigation events on Field **S4-6** of the Tareen Farm, Fields 1, 2 of the Yasin farm and Field 3 of the Nawaz farm. In Annex **1,** Annex 2, Annex 3 and Annex **4,** the simulation outputs are documented for Fields **S4-6, 1,** 2 and **3,** respectively.

In the last column of Table **4.1,** a fourth parameter has been included, called the deep percolation ratio **(DPR)**, which reflects the amount of water which is not stored in the rootzone and percolated down into the groundwater aquifer, which is considered as water losses to the farmer. The DPR is formulated as (Walker, **1989):**

$$DPR = 100 - E_a - TWR \tag{4.1}$$

Where: **DPR** = deep percolation ratio (%); 100 refers to 100%. so that E_a + TWR + DPR = 100%; E_a = application efficiency (%); and TWR = tail water ratio (%). For basins, TWR = 0 (a basin has a closed-end boundary condition).

Table 4.1. Simulated field irrigation performance for selected irrigation events on the Fields **S4-6, 1, 2,** and **3.**

	Date	Q (l/s/m)	t_{co} (min)	t_a (min)	E_a (%)	E_r (%)	DU (%)	DPR (%)
⇒ **Field S4-6**								
Event 1	25/08/95	2.0031	127	135.6	61.3	99.6	70.8	38.7
Event 2	11/09/95	2.6533	72	75	86.3	97.1	78.5	13.7
Event 3	04/10/95	2.4214	45	53.5	99.3	65	93.6	0.7
⇒ **Field 1**								
Event 1	14/01/96	1.1315	90	76.6	50.3	100	79.6	49.7
Event 2	06/02/96	1.283	44	43.2	94.9	96	84.4	51
Event 3	29/02/96	1.131	61	59.1	85.3	99.2	83.8	14.7
Event 4	12/03/96	1.1892	46	47.2	88.8	99.6	88.2	11.2
⇒ **Field 2**								
Event 1	23/01/96	1.8111	78	54.8	37.5	100	85.4	62.5
Event 3	29/02/96	1.6013	55	52.1	73.2	99.9	80.3	26.8
Event 4	12/03/96	1.581	54	45.6	72	100	88.7	28
Event 5	28/03/96	3.2626	29	29.7	45.1	100	79.6	54.9
⇒ **Field 3**								
Event 1	19/01/96	0.4148	250	24.88	84.9	95.9	75.2	15.1
Event 2	07/02/96	0.368	164	159.5	99.9	72.1	76.6	0.1
Event 3	02/03/96	0.3796	155	141.7	100	89.5	88.6	0
Event 4	17/03/96	0.4331	147	80.3	100	87.3	96.4	0

In order to describe the level of performance in terms of application and storage efficiencies, as well as distribution uniformity, guidance has been taken from Hart et. at. (1979), wherein three levels of irrigation quality parameters were distinguished (i.e. excellent, satisfactory and unsatisfactory), and six categories of irrigation performance were developed. However, modifications have been made in the interpretation of the requirement efficiency, which according to Hart et. al. (1979) is excellent when greater than 0.8 (along with $E_a \geq 0.8$ and DU $\geq$ 0.9). In this section, the E_r is carefully interpreted, and an irrigation performance is not evaluated as being good or satisfactory. when under-irrigation occurs at the tail-end of the field, since this will affect the crop yield. The following concept concerning the level of performance has been made:

The results reveal that for 66.67% of the monitored irrigation events, the irrigation clearly turned out to be either insufficient ($E_a \geq= 99\%$, $E_r < 90\%$) or excessive ($E_a < 80\%$. $E_r \geq 99\%$), of which 60% show a clear over-irrigation, and 40% show a clear under-irrigation. More specifically:

- Towards a balanced irrigation ($E_a > 80\%$. $E_r > 99\%$, DU > 83%):

>> Field *I*, Events 3 and ***4;***

Most probably, a very minor under-irrigation occurs at the tail end of the field, while some over-irrigation occurs in the head reach of the field. Hence, overall, the water loss is very modest and the under-irrigation will not have any considerable impact. The soil moisture distribution is overall satisfactory. Figure 4.1 gives a graphical presentation of a fairly balanced irrigation, based on computer simulation.

- Excessive irrigation or over-irrigation (37% $< E_a <$ 75%. $E_r \cong$ 100%. 70% < DU < 89%):

>> Field ***S4-6,*** Event *1; Field I*, Event *1;* Field 2, Events *1,* 3, ***4*** and 5.

For these irrigation events, the total amount of water applied to the field exceeded the rootzone capacity (i.e. amount of water required to refill the rootzone) and percolated "unused" to the aquifer and does not return to the main irrigation system (DPR ranging between 38.7 % to 62.5%). The extent of over-irrigation varies among the identified irrigation events, and also the level of distribution uniformity varies among the irrigation events. Overall, the soil moisture distribution is satisfactory, however, in one instance (Field S4-6, Event 1), the soil moisture distribution is quite low (i.e. DU $\cong$ 70). and in combination with over-irrigation, the overall irrigation performance is unsatisfactory.

It should be noted that an E_a of around 75% in combination with an E_r of 100% *is* considered to be not at all unsatisfactory for basin irrigation systems; however, under these circumstances, water has been wasted in terms of deep percolation. Figure **4.2** gives a graphical presentation of over-irrigation, based on computer simulation. With respect to Event **1** on Field S4-6. it should be noted that some tail-end under-irrigation also occurred.

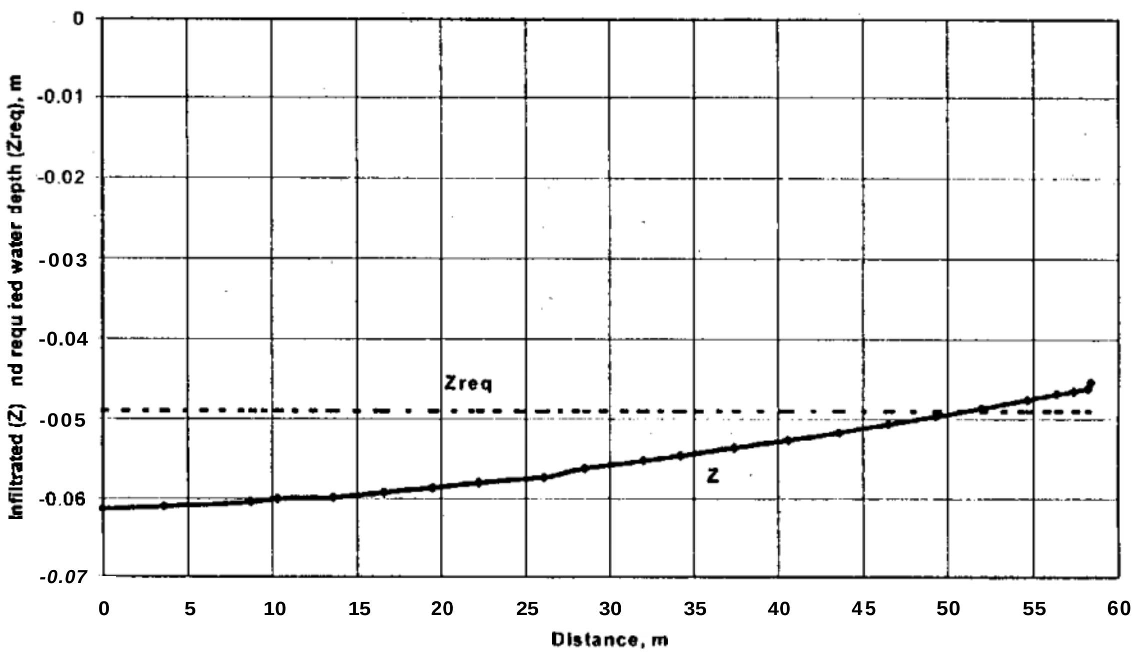


Figure 4.1. Graphical presentation of a balanced irrigation, based on Event 4 on Field 1.

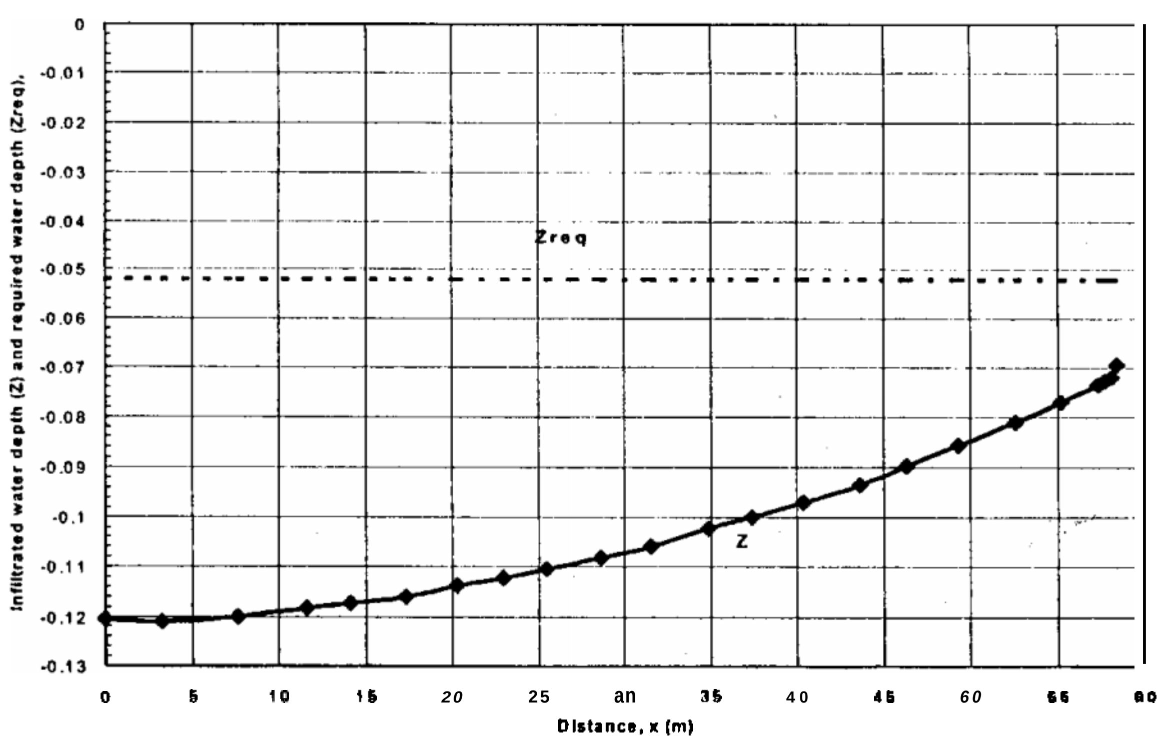


Figure 4.2. Graphical presentation of over-irrigation. based on Event 1 on Field 1.

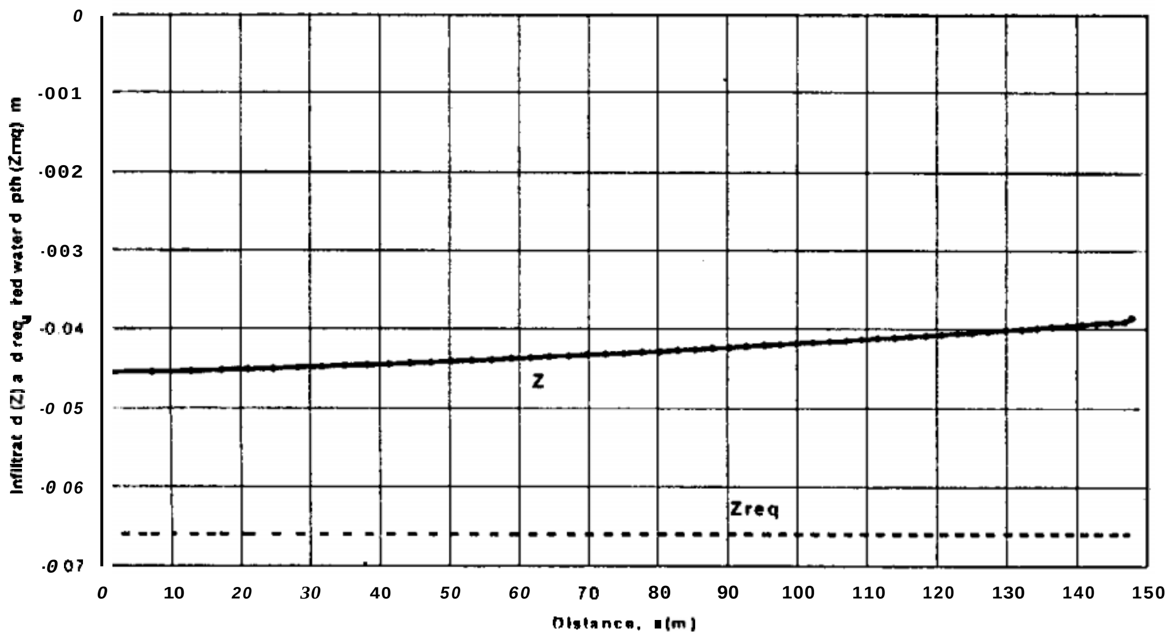


Figure 4.3. Graphical presentation of under-irrigation, based on Event 3 on Field S4-6.

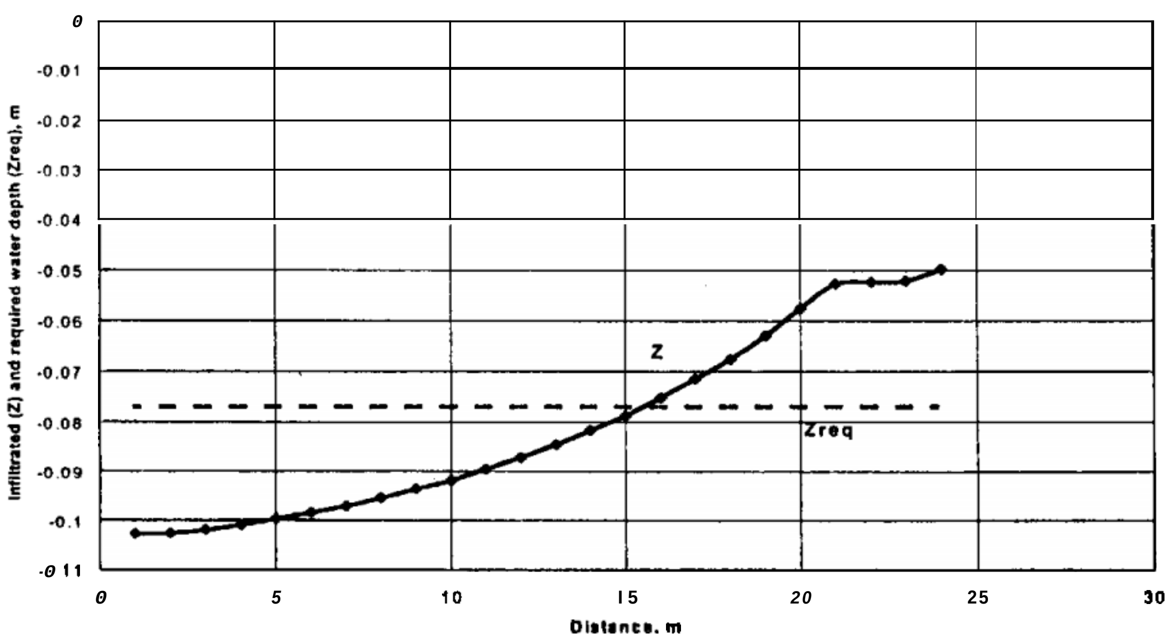


Figure 4.4. Graphical presentation of partly under-irrigation, based on Event 1 on Field 3.

- Insufficient irrigation or complete under-irrigation ($E_a \geq 99\%$, $E_r \leq 90\%$, $79.6\% < DU < 96.4\%$):

>> *Field S4-6,* Event *3; Field* 3, Events *2,* 3, ***4.***

Basically, for these irrigation events, an overall deficit of water occurs across the entire field (i.e. $Z < Z_{req}$). The applied amount of water was insufficient to cover the actual required water depth. Overall, the soil moisture distribution is ranging between excellent ($DU > 90\%$) and satisfactory ($70\% < DU < 90\%$), indicating the soil moisture has been fairly well distributed across the entire field, but yet, the water application has not been sufficient to fill the rootzone completely. Figure 4.3 gives a graphical presentation of under-irrigation, based on computer simulation.

- Tail-end or partly under-irrigation ($E_a \geq 84\%$, $E_r \leq 97\%$. $75.2\% < DU < 84.2\%$):

>> *Field S4-6,* Event 2, *Field 1,* Event *2; Field* 3, Event *1.*

Although the application efficiency has quite a high value, yet the infiltrated water depth has not met the required infiltrated water depth in the tail reach, or even over a considerable part of the field. When this practice of tail-end under-irrigation becomes a tendency, even to a small degree for even some irrigation events, under-irrigation will result in a yield reduction for the season in the lower reach of the field. For Field S4-6, Event 2 and Field 1, Event 2, the soil moisture distribution has been satisfactory, but yet insufficiently distributed at the tail reach of the field. For Field 3, Event 1, the DU is considered as satisfactory, but yet it shows the tendency towards an unsatisfactory soil moisture distribution, whereby also the water has not been properly distributed in the tail reach of the field. For the three irrigation events, the water application depth should have been slightly more in order to avoid **the** partly under-irrigation. Figure 4.4 gives a graphical presentation of tail-end under-irrigation, based on computer simulation.

In most of the instances, over-irrigation occurs for the first irrigation event, which is characterized by a much higher infiltration behavior as compared with the later irrigation events. Due to the high infiltration rate, the water advances at a very slow rate across the soil surface, and it takes a much longer time to meet the required water depth at the lower end of the field.

A note can be made for the first irrigation event on Field 3. After about five minutes of tubewell irrigation, the electricity was shutoff due to 'load shedding'. Some water had already advanced over the field. About 20 minutes later, the electricity was back and the farmer continued the irrigation event. In fact, a natural form of surge flow occurred, resulting in less infiltration in the head reach of the field. Due to this reason, some inaccuracy might have occurred in the volume balance analysis for deriving the infiltration function, and consequently, the irrigation simulation.

Although the field at the Tareen Farm has been laser leveled, the overall irrigation performance was not so good. The first irrigation suffered from over-irrigation and the following irrigation events led to under-irrigation. Also, **the** farmer has access to a neutron probe in order to keep track of the soil moisture deficit; and Cut-throat Flumes are installed for deriving the discharge flowing into the field. Despite, the availability of these techniques, the farmer has been unable to satisfactorily meet the crop water demand for the different irrigation events.

IMPLICATIONS OF THE UNSATISFACTORILY IRRIGATION PERFORMANCE

Based on this analysis, two processes were identified (i.e. the occurrence of over- and under-irrigation), which can be expected to have an impact on the agricultural production and environment. As elaborated in Kalwij (1997). the different irrigation events are applied during different crop growth stages, and each growth stage has its sensitivity towards either excessive or insufficient irrigation. The low performance of the first irrigation has an impact on the seed germination and emergence during the establishment stage. Another critical stage occurs during flowering, shortly after the third irrigation event. The frequent under-irrigation, as occurred for the irrigation events applied to Field 3 and the later irrigation events applied to Field S4-6 and Field 1, will result in lower yields at the lower end (or part) of the field. Table 4.2 presents the yield lor one square samples taken at the head, middle and tail of the Fields 1, **2** and 3.

Table **4.2.** Wheat yield data for the Fields **I ,2** and **3,**
Rabi 1995 – 1996.

Yield at:	Head (g/m^2)	Middle (g/m^2)	Tail (g/m^2)
Field I	277	**341**	458
Field 2	242	**263**	**304**
Field 3	212	176	177

Results reveal that for all of the fields, the variation in yield at the head, middle and tail of the field vary a lot. A better yield is obtained for Field 1, however, yield reduction occurs at the head of the field. This tendency can also be observed for Field 2. Field 3 shows yield reduction towards the end of the field, which is a consequence of the frequent under-irrigation. Overall, the wheat yield for Farmer Nawaz was less as compared with Farmer Yasin. This is due to a virus attack which occurred towards the end of the wheat season and damaged the wheat crop at the Nawaz Farm.

Excessive use of irrigation affects the agricultural production, but foremost, from an environmental point of view, the waste of water is a loss. Nutrients percolate downwards into the aquifers along with salts. Furthermore, if the farmer uses his water more efficiently, especially for the first irrigation. he will be able to operate the tubewell during for less time, which will save money and electricity or fuel, and he will be able to irrigate more fields during his turn.

EXTRAPOLATION TO FARM LEVEL

For the Yasin farm, some additional data were collected for the first and second irrigation events for other fields of the same farm during the same irrigation season, Rabi 1995-1996. These data are concerned with: (i) Field inlet discharge; (ii) irrigation duration; and (iii) advance time (for the total field length). The physical features of the different fields of the Yasin farm are presented in Table 4.3. These fields show the same soil physical features as either Field 1 or Field 2[7]. Based on this information, it is assumed that the calibrated infiltration functions for Fields 1 and 2 hold good for the other monitored fields on the farm. Some fields showed the same soil characteristics as identified for Field 1, and other fields showed the same soil characteristics as identified for Field 2. The hydrodynamic simulation model has been used again to assess the field irrigation performance for some of the other irrigated fields of the Yasin Farm during the first and the second irrigation events during the Rabi 1995 - 1996 season.

Table **4.3.** Physical features of selected fields of the Yasin Farm during the first and second

Yasin Farm W/C Fordwah 14-R	Date	Length (m)	Vidth m)	Discharge (l/s/m)	Cutoff time (min)	Advance time (min)
⇒Event 1						
Bunded unit 01 (1)	14/01/96	59.2	6.3	1.255	88	75
Bunded unit 02 (1)	14/01/96	58.4	18.5	1.046	83	81
Bunded unit 34 (2)	23/01/96	59.5	15.5	1.564	70	65
Bunded unit 35 (2)	23/01/96	59.5	10.2	2.38	53	40
Bunded unit 36 (2)	23/01/96	59.5	11.4	2.094	49	40
Bunded unit 37 (2)	23/01/96	59.5	12.2	1.921	58	45
Bunded unit 38 (2)	23/01/96	59.5	11.8	2.06	60	50
Bunded unit 39 (2)	23/01/96	59.5	12.9	1.885	75	50
Bunded unit 41 (2)	23/01/96	59.5	10	2.769	45	39
⇒Event 2						
Bunded unit 09 (1)	06/02/96	58.4		1.923		
Bunded unit 02 (1)	06/02/96	58.4	18.5	1.224	72	66
Bunded unit 05 (1)	06/02/96	58.4	15.2	1.46	38	31
Bunded unit 06 (1)	06/02/96	58.4	16.5	1.354	42	41
Bunded unit 08 (1)	06/02/96	58.4	11	2.079	25	22
Bunded unit 07 (1)	06/02/96	58.4	13.1	1.741	52	50
Bunded unit 04 (1)	06/02/96	58.4	17	1.325	35	28

(1) or (2) refers *to* Field *1 or* Field 2, *that indic*es which calibrated *infiltration* function is appropriate or each field.

Table 4.4 presents the results of the computer irrigation simulation. In some of the instances, the infiltration function as calibrated for the Fields 1 and 2 matched perfectly with the other

[7] Based on the field study done by the Soil Survey of Pakistan (SSP) in collaboration with IIMI-Pakistan in Ihe Tehsils of Chistian Sub-division in 1996. Additionally, SSP conducted a soil survey at the sample fans used in this study. For more details about the soil physical features of the sample fields, the reader is referred to Kalwij (1997).

fields. The simulated advance time is almost the same as the monitored advance time. In some of the instances, however, the infiltration function had to be slightly adjusted (k ad f_0 values of the Kostiakov-Lewis Equation) in order to match the predicted advance time with the monitored advance time within an acceptable range. The simulated advance time was assumed to be satisfactory when it differed with the monitored advance time between the range of 0 to 5 minutes taking into account the inaccuracy during the monitoring of the irrigation events. In a few instances, the calibrated function did not match at all, and therefore the results are not presented in Table 4.4.

Yasin Farm WIC Fordwah 14-R	Date	Simulated advance time (min)	E_a (%)	E_r (%)	DU (%)	k ($m^3/min^a/m$)	f_0 ($m^3/min/m$)
⇒ Event 1							
Bunded unit 01	14/01/96	71.0	47	100	83.8	0.00845	0.000198
Bunded unit 02	14/01/96	no *matching*					
Bunded unit 34	23/01/96	66.9	47.8	100	73.9	0.00781	0.000174
Bunded unit 35	23/01/96	37.1	41.7	100	88.6	0.00782	0.000175
Bunded unit 36	23/01/96	43.4	51.3	100	82.2	0.00078	0.000170
Bunded unit 37	23/01/96	48.6	47.1	100	82.6	0.00775	0.000168
Bunded unit 38	23/01/96	44.9	42.4	100	86.2	0.00785	0.000178
Bunded unit 39	23/01/96	50.4	37	100	86.8	0.00781	0.000174
Bunded unit 41	23/01/96	31.4	42.3	100	89.5	0.00790	0.000183
⇒ Event 2							
Bunded unit 09	06/02/96	29	85.9	100	91.6	0.00479	0.000176
Bunded unit 02	06/02/96	no *matching*					
Bunded unit 05	06/02/96	37.3	96.8	96	86.7	0.00470	0.000167
Bunded unit 06	06/02/96	40.8	94.8	96.6	85.4	0.00477	0.000174
Bunded unit 08	06/02/96	26.6	100	92.5	89.7	0.00470	0.000167
Bunded unit 07	06/02/96	no *matching*					
Bunded unit 04	06/02/96	no *matching*					

With respect to the second irrigation. Bunded Unit 9 shows an quite balanced irrigation, not resulting is much water losses. nor did there occur any form of under-irrigation. Additionally. the soil moisture distribution is good for Bunded Unit **9.** Although for the remaining bunded units, the application efficiency can be rated as good and very little amounts of water are wasted; under-irrigation occurs for these bunded units for the second irrigation event. The Bunded Units **5** and 6 have been partly under-irrigated, but Bunded unit 8 has been entirely under-irrigated. The soil moisture distribution is fairly good for the second irrigation on these bunded units. Apparently, under-irrigation for later irrigation events is a common tendency, practiced by the farmer, and which - as discussed earlier in this chapter - will have an impact on the yield.

MODEL VERIFICATION

Model verification has been accomplished **by** comparing the simulated advance phase with the monitored advance phase. The results are graphically presented in Figures **4.5 – 4.8** for the selected irrigation events on Field 1, Figures **4.9 – 4.12** for the selected irrigation events on Field 2, and Figures **4.13 – 4.16** for the selected irrigation events on Field **3.** The data are converted from advance distance into wetted area. This was done because of the irregular tendency of the monitored advance trajectory. The monitored advance distance is based on the advance time related to covering a grid (i.e. a field is divided into a grid structure to facilitate the monitoring). In other words, during the monitoring, the irregular tendency of the advancing front has been taken into account. For Field **S4-6,** details on the advance trajectory at different distances from the field inlet were not collected.

The results reveal that the advance phase is satisfactorily simulated. Some differences occur, whereby, at certain points in the field. the simulated advance does not match the predicted advance. However, field data extrapolation may have its impact, too.

Basically. these types of basins with too many irregularities are quite difficult to simulate, because of the assumptions made in the simulation model and its simulation per unit width only. However. the main constraint with small basins **is** an irregular topography, resulting in a difficult determination of the advance function, which causes instability in the simulation. This was especially the case for Field **1** and 2. Field S4—6 and Field 3 showed much better stability in terms of advance and infiltration flow. Both fields are relatively large and the field topography was much better.

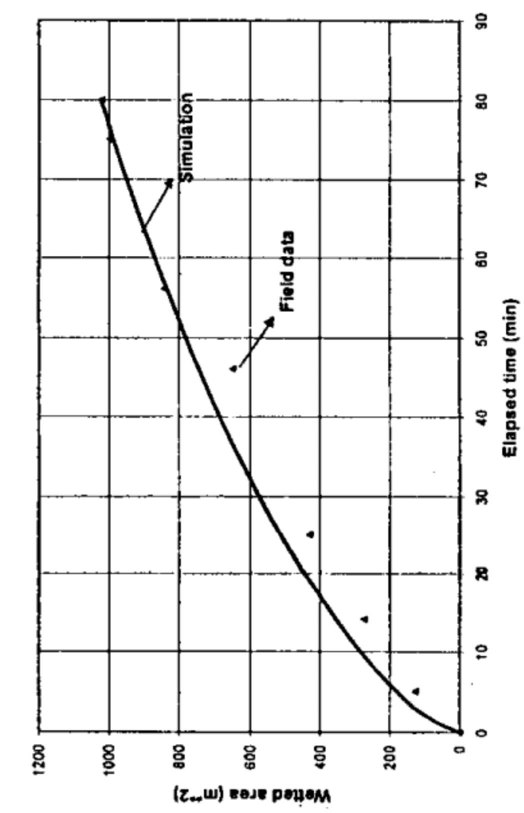


Figure 4.5. Monitored and simulated advance phase for Event 1 on Field 1.

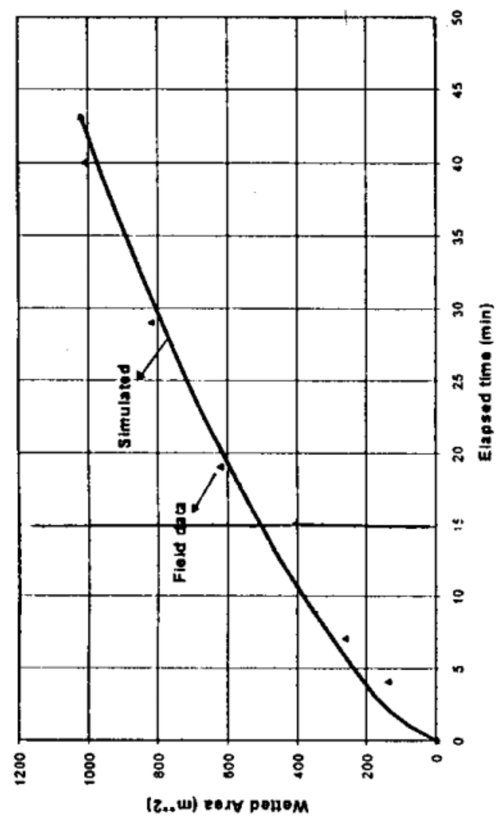


Figure 4.6. Monitored and simulated advance phase for Event 2 on Field 1.

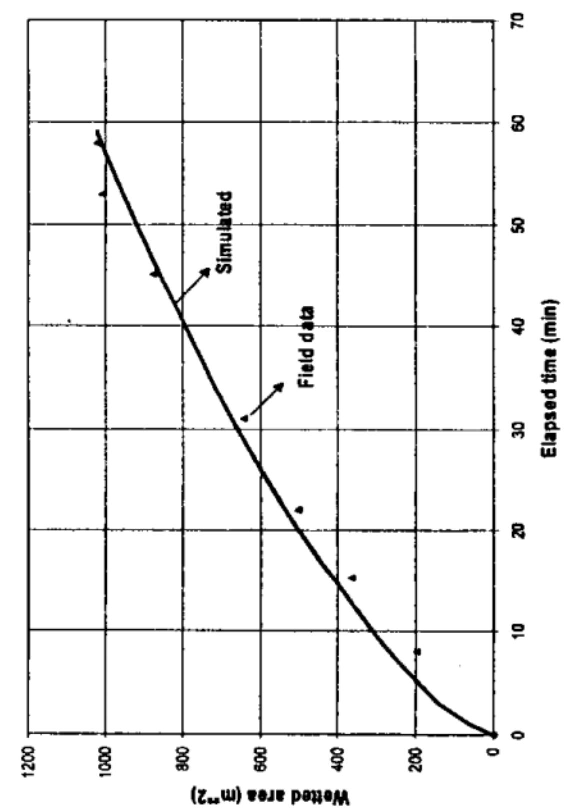


Figure 4.7. Monitored and simulated advance phase for Event 3 on Field 1.

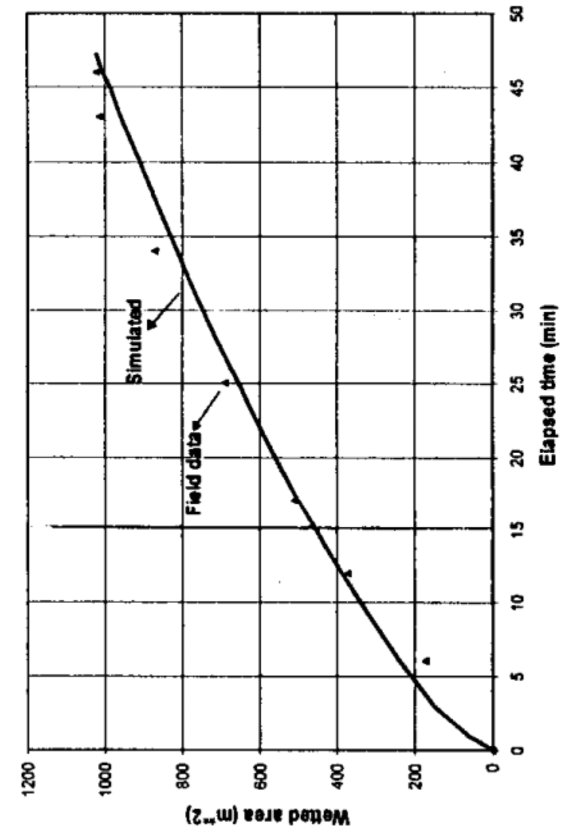


Figure 4.8. Monitored and simulated advance phase for Event 4 on Field 1.

Figure 4.9. Monitored and simulated advance phase for Event 1 on Field 2.

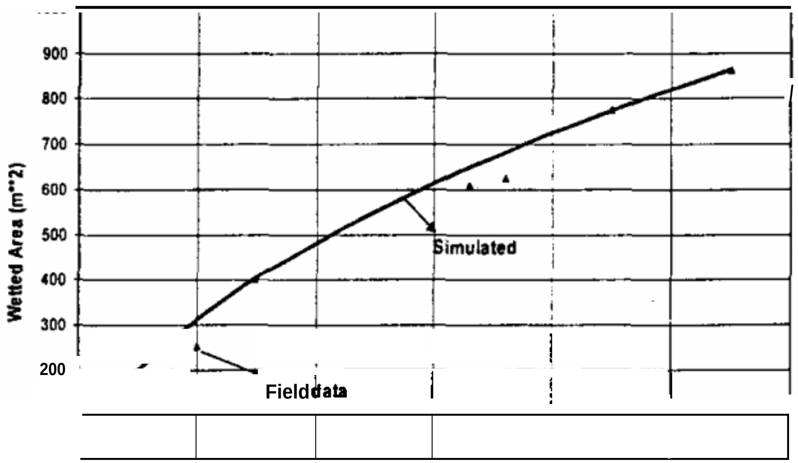


Figure 4.10. Monitored and simulated advance phase for Event 3 on Field 2.

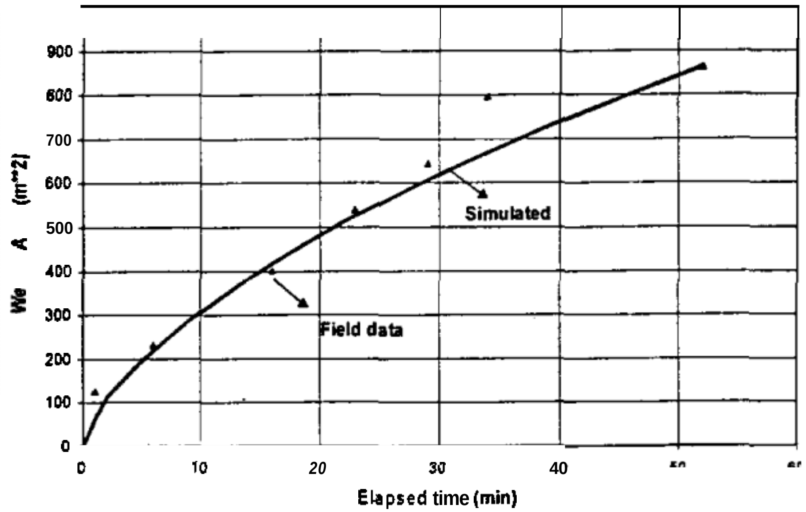


Figure 4.11. Monitored and simulated advance phase for Event 4 on Field 2.

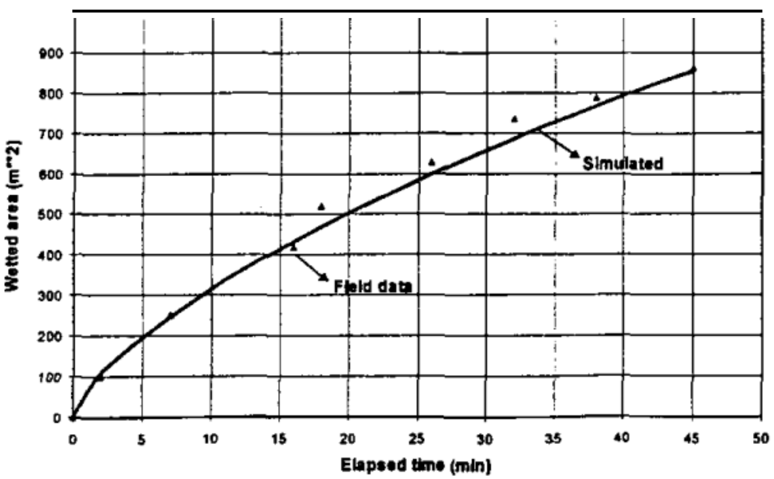


Figure 4.12. Monitored and simulated advance phase for Event 5 on Field 2.

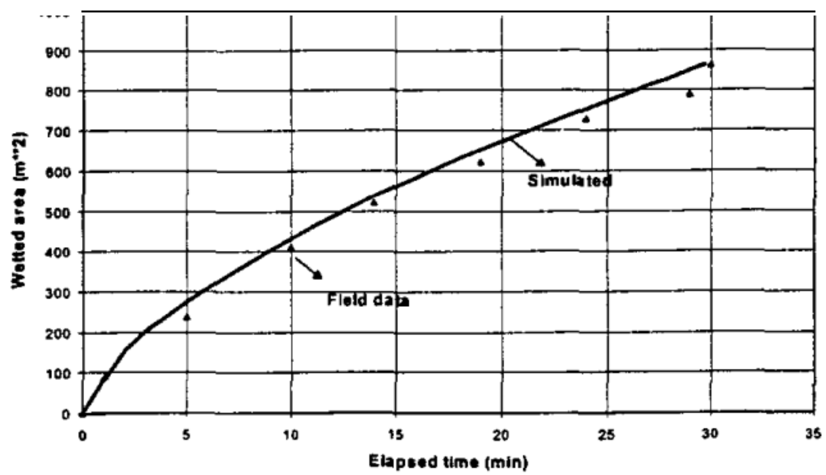


Figure 4.11. Monitored rod simulated advance phase for Event I on Field 3.

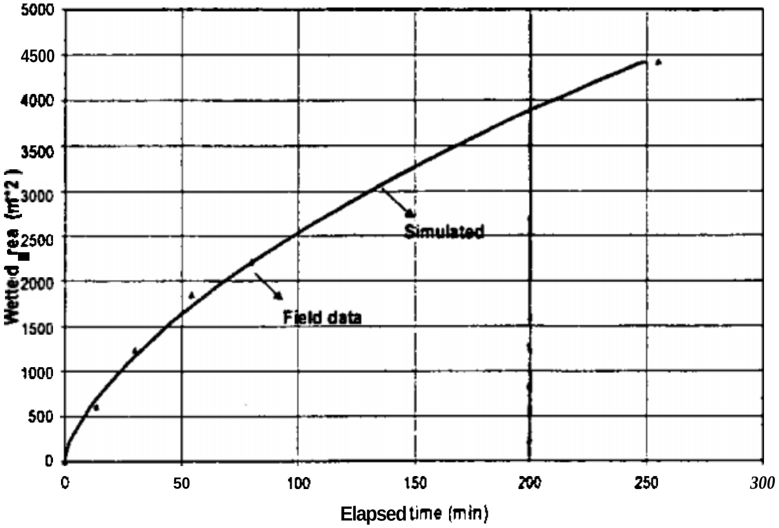


Figure 4.14. Monitored and simulated advance phase for Event 2 on Field 3

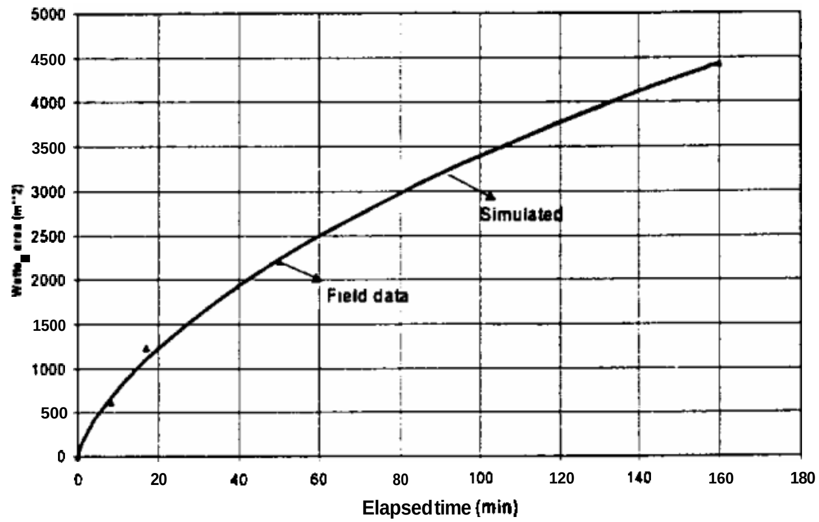


Figure 4.15. Monitored and simulated advance phase for Event 3 on Field 3.

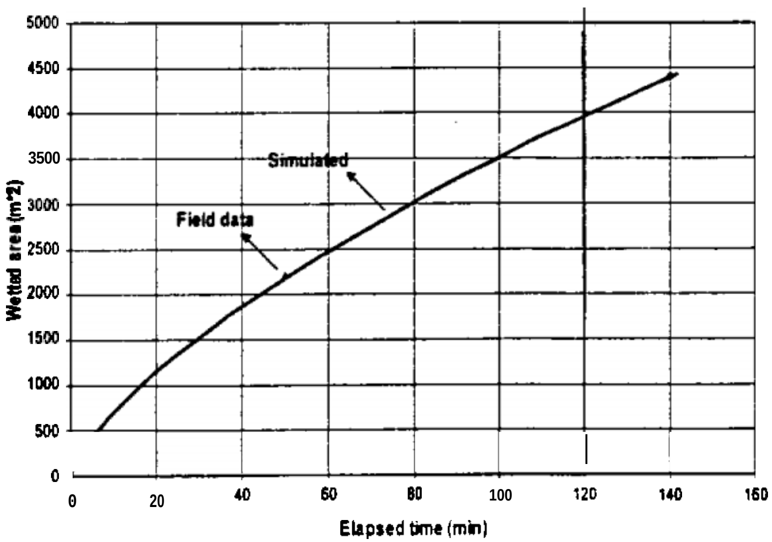
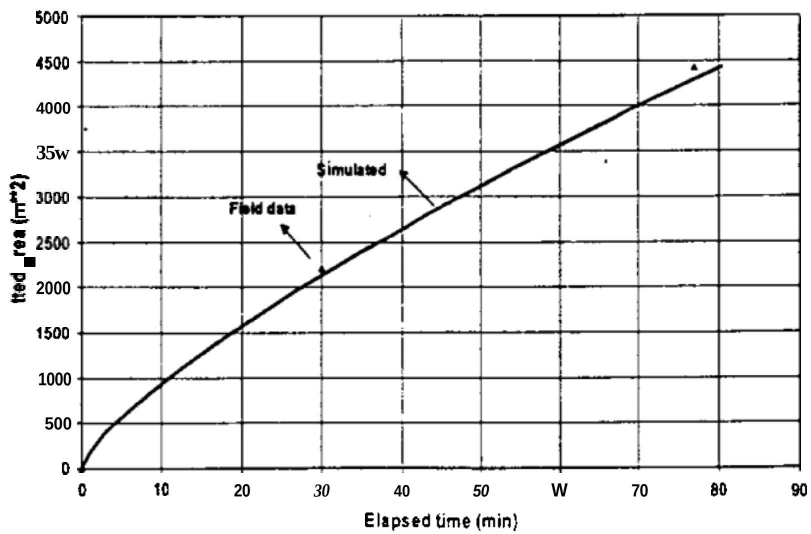


Figure 4.16. Monitored and simulated advance phase for Event 4 on Field 3.



CHAPTER V OPTIMIZATION AND MANAGEMENT OPTIONS

FARMERS' DECISION MAKING: FIELD OBSERVATIONS

At the Tareen Farm, the landholding is divided into large fields or blocks of 10 acres size or 20 acres size. Each block is divided into two parts and each part is divided in about six bunded units (i.e. the trial fields). A part of the land is irrigated by the basin irrigation method (i.e. flat basins), and a part is irrigated by the bed - and - furrow irrigation method (either zero-slope or a 0.0001 slope). Mostly, a group of bunded units is irrigated at the same time. Several field inlets serve a bunded unit. A few laborers are responsible for the irrigation. In order to decide when to irrigate. the irrigation practices aro closely monitored by the farm managers present at the Tareen Farm. Wilh the help of a neulron probe device. the soil moisture profile is closely monitored, along with checking the surface soil and crop condition (a 40% soil moisture depletion level is maintained). Additionally, the flow measurement device provides the information on the available discharge, and, thus, an estimate is made on how long to irrigate. Despite all of these available techniques, it turns out to be quite difficult to obtain a good irrigation performance (see Chapter IV). As indicated in Chapter I, the Tareen Farm has a continuous water supply, either canal water or tubewell water. A part of the water supply is collected in a tank, and is pumped into the main (farm) channel when an irrigation event to take place.

In the case of the Yasin Farm and the Nawaz Farm, the landholding is divided into small bunded units[8]. The Yasin Farm shows the typical characteristics of a small farmer with no machinery. Land preparation, planking, etc. is done by animal traction and he prefers to make small basins. Although he is supposed to receive water from the canal, he relies more on, and uses more of, the tubewell water (especially during the rabi irrigation season). Since the design discharge of the tubewell is small (i.e. ± 1 cusec) the farmer prefers smaller basins. However, he also shows his hesitation to make the bunded units smaller, because it will increase the number of bunded units to irrigate and, hence, it will increase the work load. He does not have regular laborers who assist him during the irrigation events. Quite oflen, he opens two or three field inlets at the same time, goes away or goes to sleep, and then changes the rotation afler some time. Nevertheless, the general tendency is to irrigate.until the water reaches the end of the field;

[8] **More precisely, a farm consists of several *kilas.* which is a** local **Pakistani measure which equals slightly less than one acre. Each kila is sometimes completely used as one basin, or more frequently is divided into smaller units. The criteria used by the farmer to decide the number of divisions is related to the soil type and equipment used for the cultural practices. Generally, lighter soils are divided into smaller portions compared with heavier soils. Furthermore. when proper leveling equipment is not available, the farmer has the tendency to divide his farm into smaller units in order to reduce the irregularities. Farmers who are dealing with farm mechanization are more inclined towards making large units, which is considered as being more practical when using machinery.**

however, the first irrigation events require considerable time, which also occurs sometimes for later irrigation events.

Mr. Nawaz is an irregular irrigator. He always takes his chances as to when the actual owner does not use the tubewell. Besides, he is not limited to a ***warabandi***. Due to the landowner, he has access to machinery for land preparation, leveling (not laser-controlled leveling), etc. This is the main reason why he prefers to keep the basins large, despite the low average field inlet inflow of less than 0.5 l/s/m. The soil shows a low infiltration. mainly due to the combination of a loam soil and an alkali crust. It takes days before the water is drained off the field. Also, it takes him a long time to irrigate. Since quite often he is confined to night irrigation. he opens several field inlets and goes to sleep. or does quick irrigation events in order to avoid the all-night-through irrigation events. Basically, it is Ihe son of Mr. Nawaz who generally takes care of the irrigation events. The general applied irrigation practice is to irrigate longer than the total advance time.

Both of the farmers (Mr. Yasin and Mr. Nawaz) have their limitations in terms of field length due to the natural land division. Mostly, fields are not longer than 70 meters. Both farmers are using tubewell water. which according to the farmers, hardens the soil surface and a crust remains at the soil surface. Both prefer canal water above tubewell water, which is considered as "softer" and of better quality. The Nawaz Farm shows some salt patches. while no salt hazard has been observed at the Yasin Farm.

MAXIMIZING APPLICATION EFFICIENCY THROUGH DESIGN VARIABLE MODIFICATIONS

Simulation procedure

Managing the irrigation water is a precise task and a lot of effort has to be undertaken to make sure that either not too much or too little water is applied. Basically, a farmer needs to know how much water is required (i.e. crop water requirement), along with how long to irrigate. These are two crucial components for a good irrigation event, yet difficult for the farmer to know. For this reason, farmers are entirely dependent on experience and personal judgement.

The evaluation results for the four,fields reveal that the farmers have difficulties with applying the exact amount of water needed. Farmer Tareen faces over-irrigation along with tail-end under-irrigation for the first irrigation event, followed by under-irrigation for the second and third irrigation events. Farmer Yasin faces quite some instances of over-irrigation and also some under-irrigation, whereas Farmer Nawaz has more of a problem in mainly under-irrigating a part of the field as well as the tail end of the field only.

The hydrodynamic simulation model has been used for analyzing the discharge - application efficiency relationship. For this purpose, different field inlet inflows were used, corresponding to a specific field width. For maximizing the application efficiency, the main criteria used was to maximize the requirement efficiency till it was exactly 100%. In other words, many iterations were made wherein the cutoff time was modified till the desired requirement efficiency of 100% was reached, but not exceeding **100%.**

The results of the simulations are graphically presented in Figures **5.1** to **5.4** for Field **S4-6,** Field 1, Field 2 and Field 3, respectively. Additionally, the computer simulation results are summarized in Tables **5.1** to **5.4** for Field **S4-6,** Field **1,** Field 2 and Field 3, respectively, including the cutoff and advance time.

Discharge – application efficiency relationship

The graphs reveal that, by increasing the field inlet inflow, the application efficiency increases too, which holds good with what has been stated in FAO Paper **45** (Walker, 1989): "that because there is no tailwater problem, the maximum unit inflow also maximizes application *efficiency*".

The graphs also reveal that the first irrigation events have a lower application efficiency as compared with the later irrigation events. This phenomenon is related to the extremely high infiltration rate for the first irrigation events, compared with the later irrigation events.

Further, by comparing the overall achieved maximized irrigation performance for the different sample fields, the following statements can be made.

- At Field **S4-6** and Field **3,** higher application efficiencies can be achieved as compared with Fields **1** and 2. The cause can be ascribed to the soil surface condition. At the Nawaz Farm, the land is properly leveled during the land preparation in order to obtain a leveled and smooth soil surface. At the Tareen Farm, laser leveling is applied in order to level and smoothen the soil surface and further, a proper compaction is done. Further, both of the fields show a relatively lower infiltration behavior as compared with Fields **1** and 2, which has an impact on the irrigation performance. However, it should be noted that the average field inlet discharge is much higher for Field **S4-6** as compared with Fields 1, 2 and 3, and consequently, higher efficiencies can be achieved.

- During the third irrigation event at the Tareen Farm, the infiltration behavior is very low. This has a consequence in that the application efficiency does not change when the simulated field inflow per unit width is changed. Basically, during this irrigation event, the major changes occur in the soil moisture distribution, which become better when the simulated field inlet inflow increases. In other words, the lower the infiltration behavior is, the less sensitive the application efficiency becomes for the applied discharge.

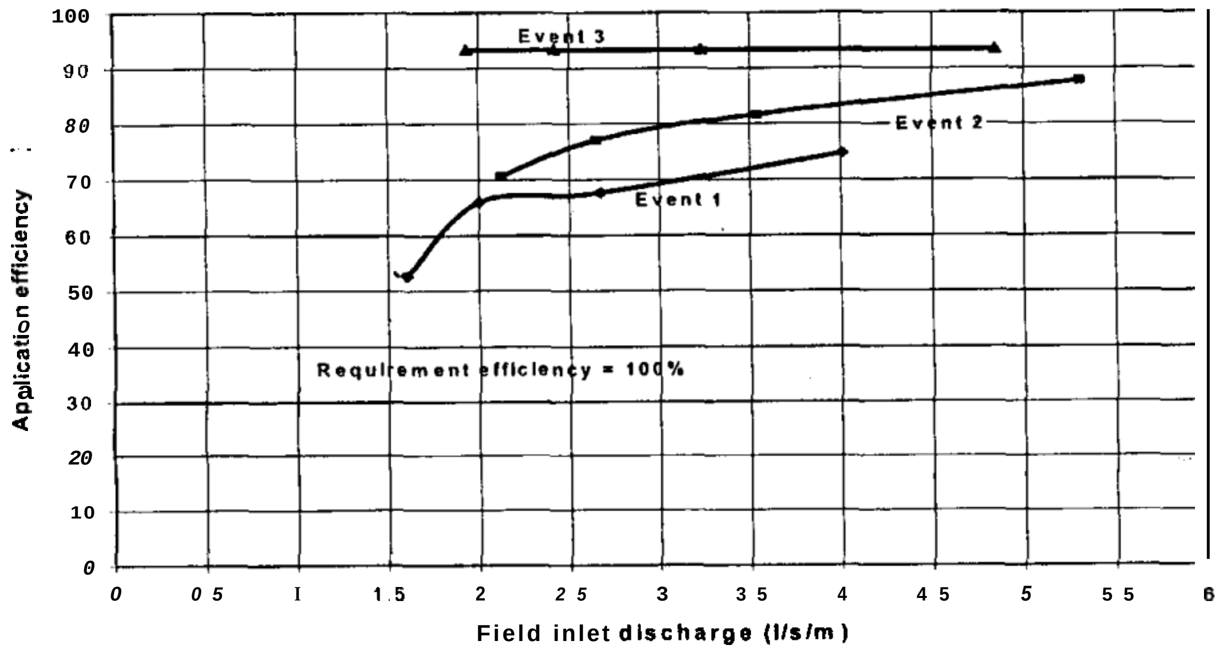


Figure 5.1. Maximum application efficiency for different field inlet discharges for selected irrigation events on Field S4-6 of Tareen Farm, Kharif 1995 irrigation season.

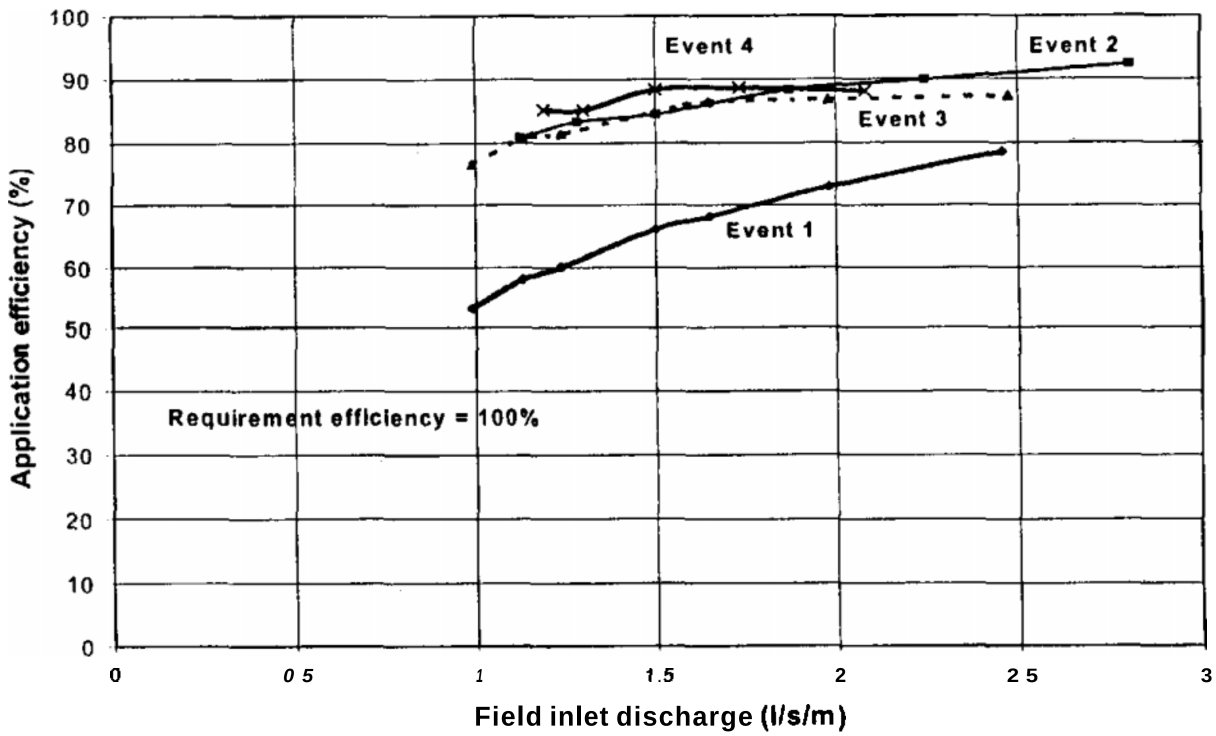


Figure 5.2. Maximum application efficiency for different field inlet discharges for selected irrigation events on Field 1 of Yasin Farm, Rabi 1995 – 1996 irrigation season.

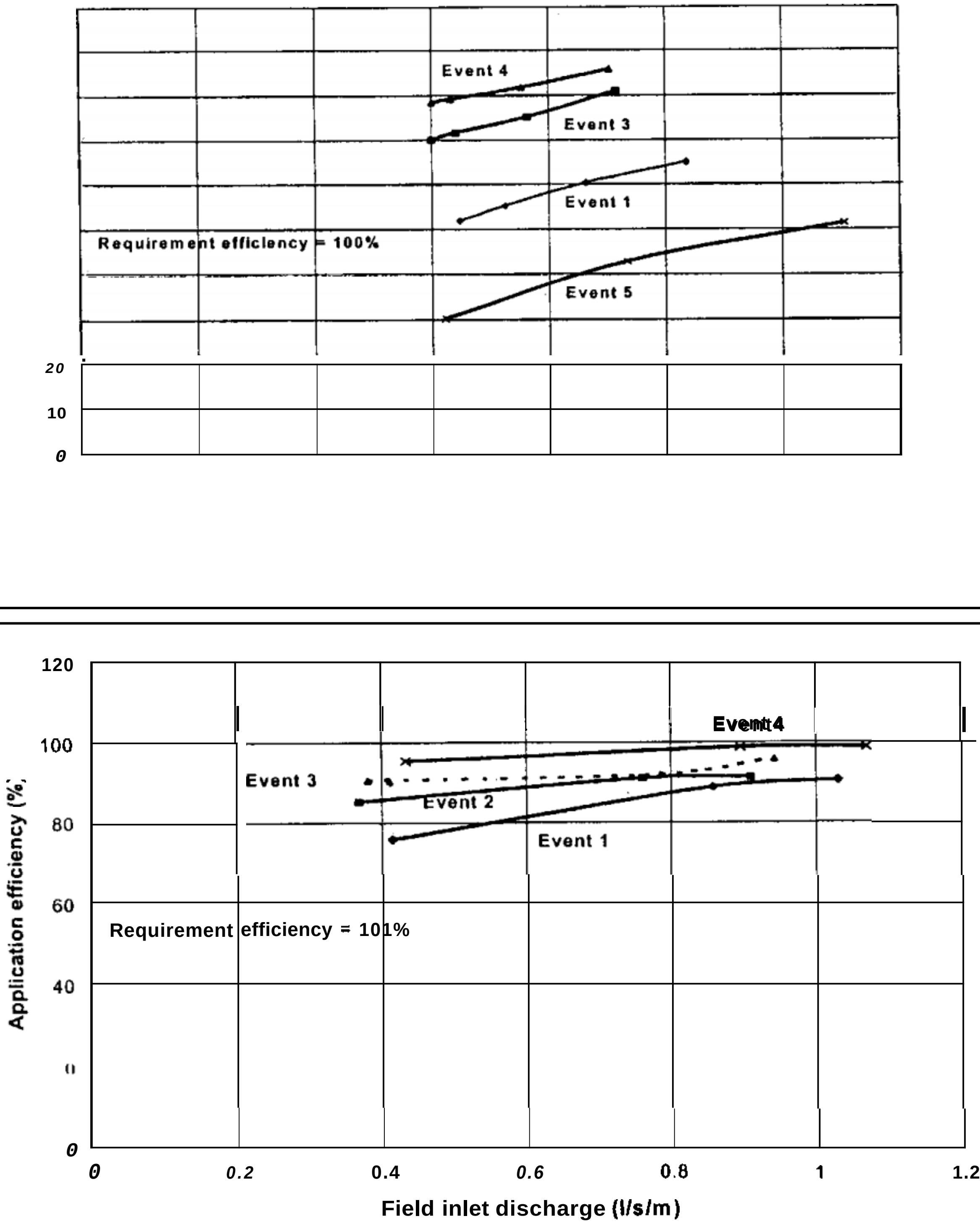


Figure 5.4. Maximum application efficiency for different field inlet discharges for selected irrigation events on Field 3 of Nawaz Farm, Rabi 1995 – 1996 irrigation season.

Interrelation between the desian variables

In Tables 4.1 and 4.2, the design variables are summarized (discharge and cutoff time) along with the predicted advance time for the Fields S4-6, 1, 2 and 3, respectively.

The results reveal that there is a clear interrelation between the design variables, cutoff time (t_{co}), the field inlet discharge (Q), and the advance time (t_a), showing a decreasing

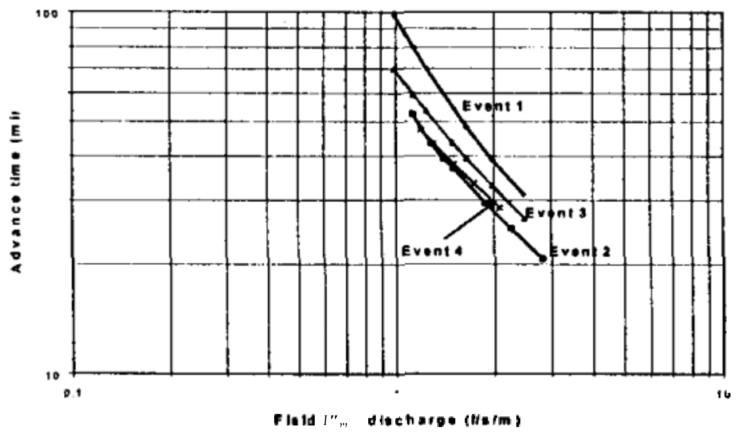


Figure 5.5. Discharge – advance relationship for selected irrigation events on Field 1 of the Yasin Farm.

Table 5.1. Maximum application efficiency for different field inlet discharges and the corresponding cutoff and predicted advance time for selected irrigation events on Field *S4-6* of the Tareen Farm. Kharif 1995 irriaation season.

FW m)	Q (l/s/m)	t_{co} (min)	t_a (min)	E_a (%)	E_r ("fa)	DU (%)
Field S4-6	Event 1	*25/08/95*				
29.72	4.0062	53	59.4	74.5	100	84.4
44.58	2.6708	88	92.1	67.6	100	77.8
59.44	2.0031	131	135.5	65.9	100	73.6
74.3	1.6025	186	147.8	52.6	100	69.4
Field S4-6	Event 2	*12/09/95*				
29.72	5.3066	37	37.1	87.7	100	90.5
44.58	3.5377	59	54.6	81.6	100	86.9
59.44	2.6533	83	75.2	77	100	83.5
74.3	2.1226	113	100.5	70.5	100	80.3
Field S4-6	Event 3	*04/1 Of95*				
29.72	4.8428	37	34	93.3	100	96.3
44.58	3.2285	55	44.1	93.3	100	95.7
59.44	2.4214	73	53.6	93.3	100	95.2
74.3	1.9371	91	62.7	93.3	100	94.8

Table **5.2.** Maximum application efficiency for different field inlet discharges and the corresponding cutoff and predicted advance time for selected irrigation events on Field **1** of the

FW (m)	Q (l/s/m)	t_{co} (min)	t_a (min)	E_a (%)	E_r (%)	DU (%)
Field **1**	Event **1**	***14/01/96***				
20	0.99	97	97.7	53.2	100	70.7
17.5	1.1315	78	79.6	58.1	100	72.6
16	1.238	69	69.9	60.1	100	75
13.2	1.5	52	54.1	66.2	100	77.7
12	1.65	46	48.1	68.2	100	79.3
10	1.98	36	39	73	100	81.1
8	2.457	27	31.1	78.6	100	83.5
Field **1**	Event **2**	**06/02/96**				
20	1.123	58	52.4	80.9	100	84.7
17.5	1.283	52	43.3	83.3	100	87.9
16	1.403	47	39.3	84.5	100	89
15	1.5	44	36.7	84.5	100	89.6
12	1.871	34	29.6	88.3	100	91
10	2.245	28	25.2	89.9	100	92.4
8	2.807	22	20.8	92.4	100	93.4
Field **1**	Event **3**	***29/02/96***				
20	0.99	78	69.4	76.6	100	84
17.5	1.131	65	59.1	80.6	100	85.4
16	1.237	59	53.3	81.4	100	87
13.2	1.499	47	43.3	84.7	100	88.7
12	1.649	42	39.3	86.4	100	89.7
10	1.979	35	32.9	86.8	100	91
8	2.474	28	26.8	87.4	100	92.6
Field **1**	Event 4	***12/03/96***				
17.5	1.1892	48'	47.3	85.3	100	89
16	1.301	44	43.4	85.2	100	89.9
13.9	1.5	37	38	88.3	100	90.8
12	1.734	32	33.5	88.7	100	91.5

The sensitivity of the advance time towards changes in the discharge is the most for the first irrigation event, compared with the later irrigation events. This is related with the infiltration behavior of the first irrigation event, which is much higher and inconsistent as compared with the later irrigation events.

Based on the performed simulations, as presented in this paragraph, clear relationships between (i) the design variables, Q and t_{co}, and the advance time t_a; and (ii) between the design variable, Q, and the performance indicators have been identified. These relationships are of fundamental importance and have to be taken into account when improved management strategies are developed.

Table 5.3. Maximum application efficiency for different field inlet discharges and the corresponding cutoff and predicted advance time for selected irrigation events on Field 2 of the Yasin Farm, Rabi 1995 – 1996 irrigation season.

FW m)	Q (l/s/m)	t_{co} (min)	t_a (min)	E_a (%)	E_r (%)	DU (%)
Field 2	Event I	23/01/96				
16	1.619	63	64.9	52.1	100	69.2
14.3	1.811	53	54.7	55.5	100	71.7
12	2.158	41	42.9	60.5	100	75.2
10	2.590	32	34.2	65.1	100	78.2
Field 2	Event 3	29/02/96				
12.3	1.496	61	56.8	70.3	100	79.7
14 3	1.601	56	52.1	71.9	100	80.8
12	1.908	45	41.9	75.4	100	83.7
10	2.289	35	34.1	81.3	100	85.4
Field 2	Event 4	12/03/96				
15	1.500	52	48.3	78.8	100	85.4
14.3	1.581	49	45.6	79.5	100	86.1
12	1.884	40	3.9	82.1	100	88.3
10	2.261	32	31.6	86	100	89.4
Field 2	Event 5	28/03/96				
30	1.555	88	91.9	30.5	100	60.3
20	2.333	42	46.3	43.1	100	67.3
14.3	3.263	25	30.4	51.5	1no	71.1

Table 5.4. Maximum application efficiency for different field inlet discharges and the corresponding cutoff and predicted advance time for selected irrigation events on Field 3 of the Nawaz Farm, Rabi 1995 – 1996 irrigation season.

FW (m)	Q (l/s/m)	t_{co} (min)	t_a (min)	E_a (%)	E_r (%)	DU (%)
Field 3	Event 1	23/01/96				
62.05	0.415	292	246.6	76	100	89.5
30	0.858	122	97	88.8	100	91.5
25	1.03	99	78.3	90.6	100	93.1
Field 3	Event 2	07/02/96				
62.05	0.368	266	156.2	85.3	100	89.8
30	0.761	121	67.2	91.1	100	95.2
75	0.91	101	56.6	91.4	100	95.7
Field 3	Event 3	02/03/96				
62.05	0.38	192	142.2	90.6	100	92.7
30	0.786	95	68.8	92.1	100	96.1
25	0.943	76	58.6	96	100	96.4
Field 3	Event 4	17/03/96				
62.05	0.433	177	80.6	95.6	100	97.4
30	0.896	86	47.6	99	100	98.2
25	1.07	72	42.2	99	100	98.2

MANAGEMENT OPTIONS AND THEIR IMPACTS

To design management options which may lead to either saving water or guaranteeing a sufficient irrigation for the entire field, different aspects have to be considered, related to the physical environment, as well as farmers' constraints and wishes.

Through running the hydrodynamic model for different discharges for the selected irrigation events on the sample fields, it was observed that an increase in discharge results in an increase in the application efficiency. However, in order to know which discharge is advisable from a hydraulic point of view, the advance behavior is examined next. Based on the simulations as presented in Figures 5.1 to **5.4** and Tables **5.1** to **5.4,** the advance trajectory has been plotted against the elapsed time. This has been done for the first two irrigation events on Field **S4-6,** Field **1,** Field 2 and Field 3, respectively. The results are presented in Figures 5.6 to 5.13.

From the graphs, it can be clearly derived that for higher discharges, the advance phase has a more stable pattern in terms of flow velocity as compared with lower discharges. A reduction in the advance velocity has its impact on the hydraulic performance, due to the relatively longer time period before the required water depth has been achieved at the lower end of the field. A phenomenon which has been observed earlier.

Two scenarios are examined: (i) modifying the cutoff time only, while keeping the practiced discharge; and (ii) modifying the inflow per unit width along with the cutoff time.

Modifying the cutoff time only

Table 5.5 presents the results on modifying the cutoff time. The value between the brackets presents the original time of cutoff. The results reveal that water saving is accomplished for the over-irrigation cases by reducing the cutoff time, whereas for the under-irrigation cases, some of the application efficiency has to be sacrificed in order to meet the full crop water requirement at the tail area of the field.

Only in the case of over-irrigation, the modification (i.e. decrease) of the cutoff time yielded some water savings:

- Field **S4-6;** Event 1: a **4.6%** water saving per unit width could be achieved.
- Field 1; Event 1: a 7.8 **%** water saving per unit width could be achieved.
- Field 2; Event 1: a **18%** water saving per unit width could be achieved.
- Field 2; Event **4:** a 7.3 **%** water saving per unit width could be achieved.
- Field 2; Event 5: a **10.4%** water saving per unit width could be achieved.

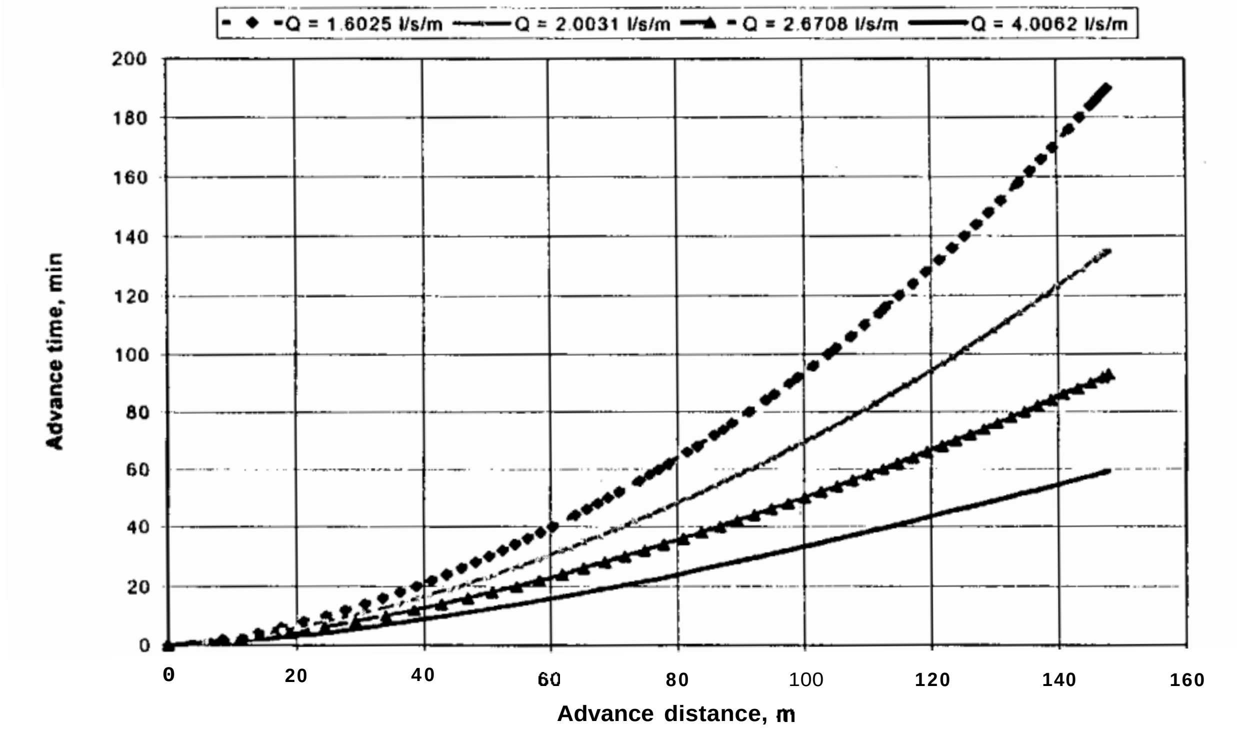


Figure 5.6. Simulated advance phase for selected discharges for the first irrigation event on Field S4-6, Tareen Farm.

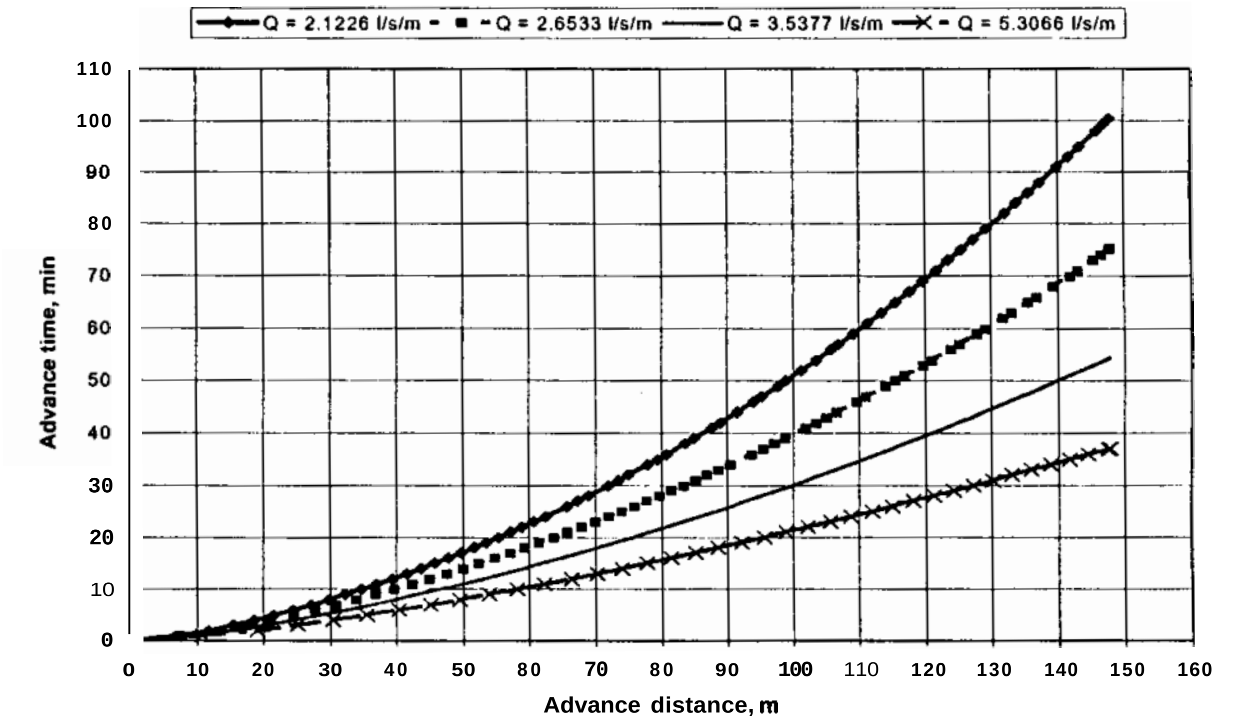


Figure 5.7. Simulated advance phase for selected discharges for the second irrigation event on Field S4-6, Tareen Farm.

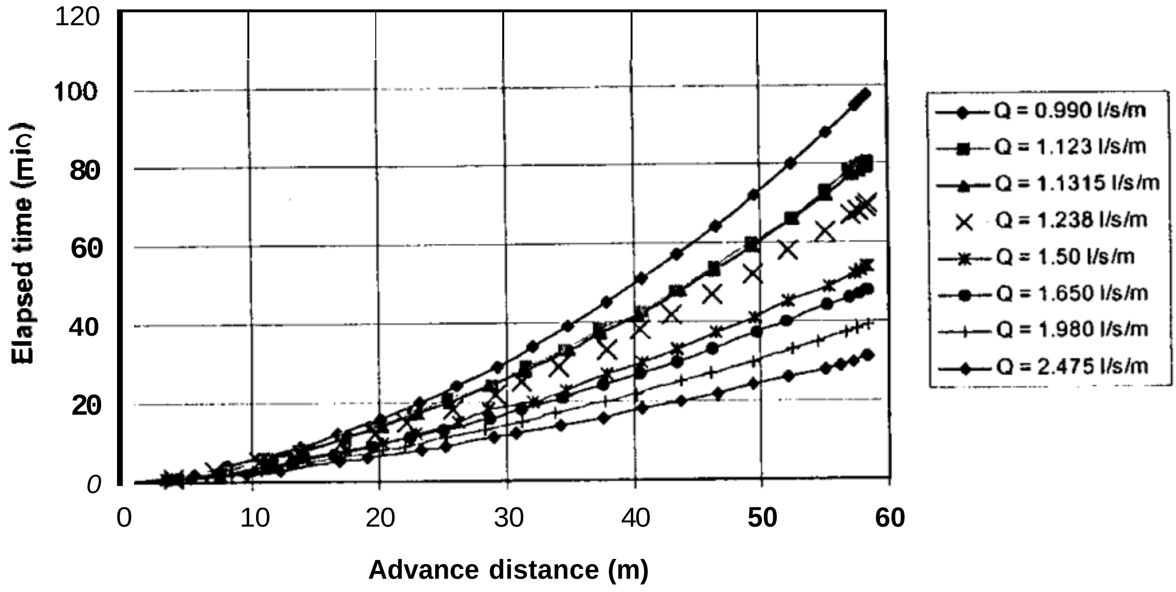


Figure 5.8. Simulated advance phase for selected discharges for the first irrigation event on Field 1, Yasin Farm.

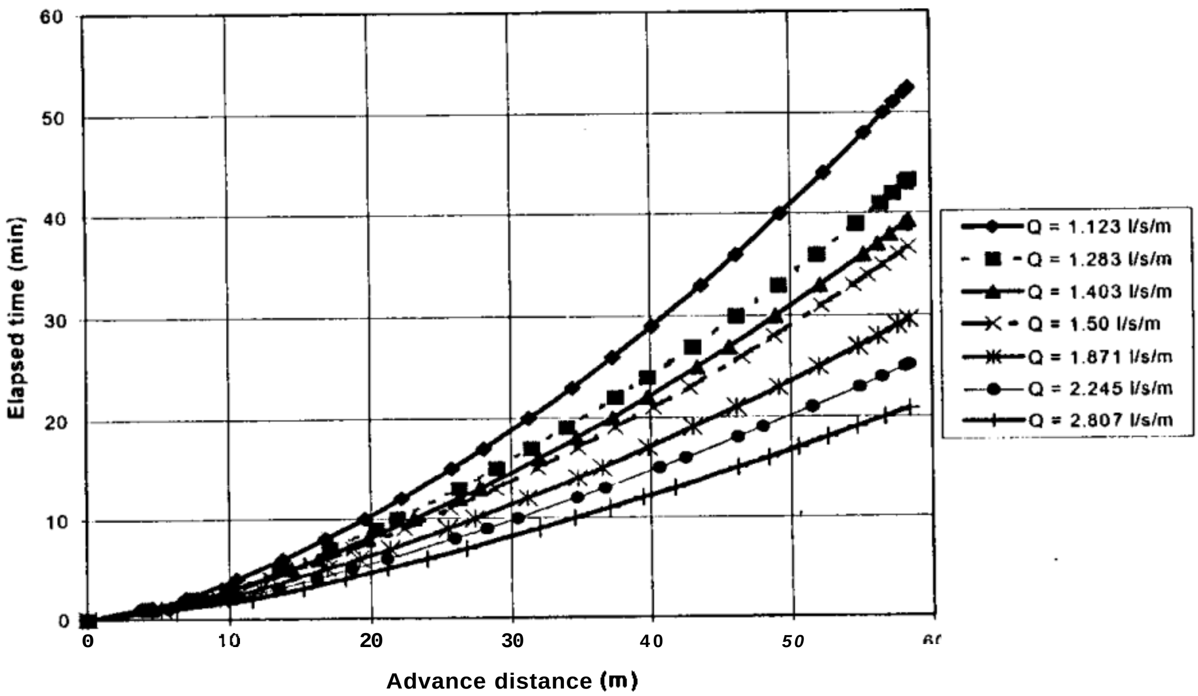


Figure 5.9. Simulated advance phase for selected discharges for the second irrigation event on Field 1, Yasin Farm.

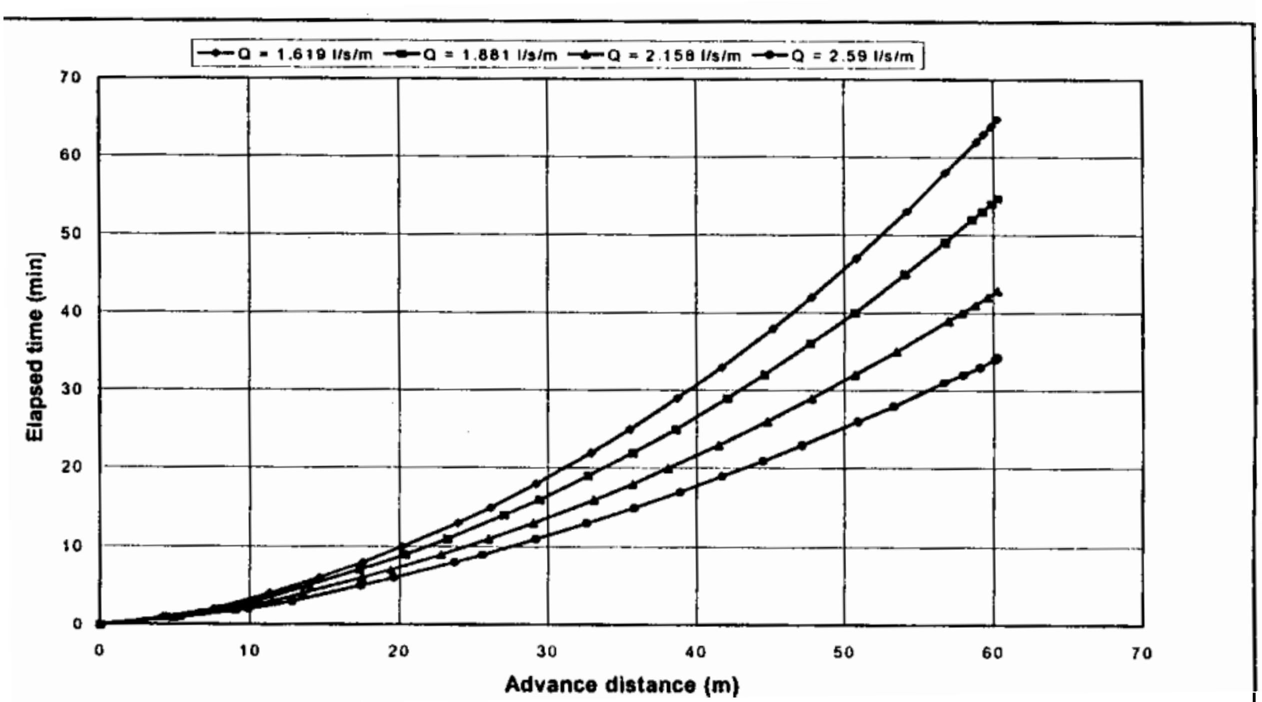


Figure 5.10. Simulated advance phase for selected discharges for the first irrigatlon event on Field 2, Yasin Farm.

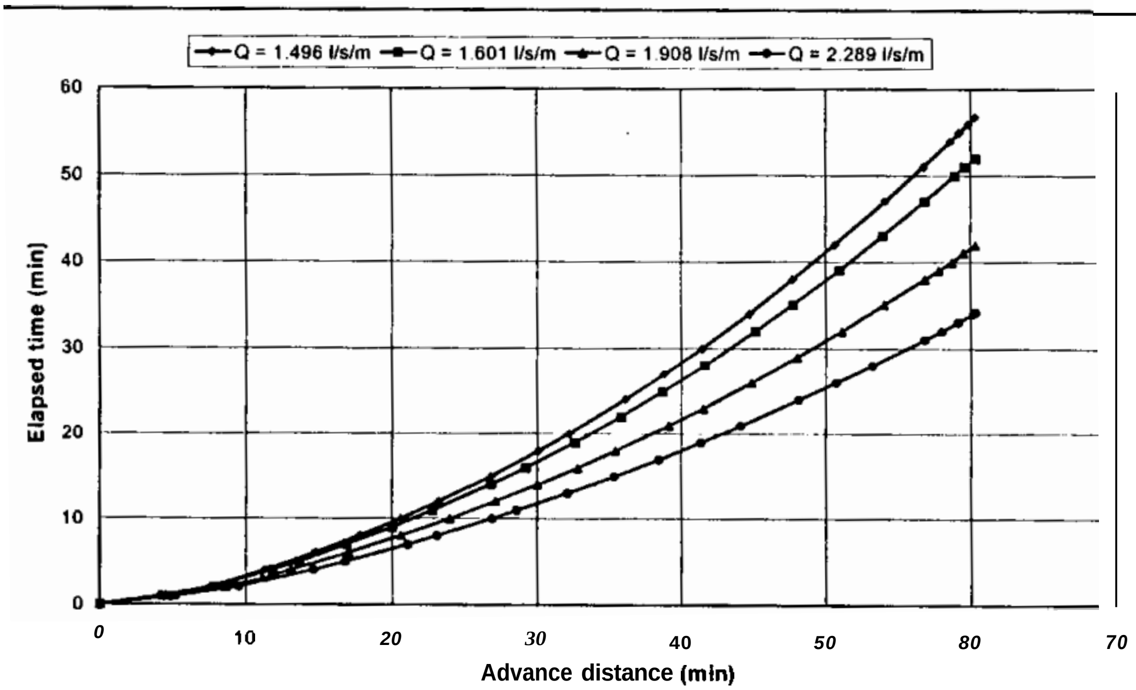


Figure 5.11. Simulated advance phase for selected discharges for the third irrigation event on Field 2, Yasin Farm.

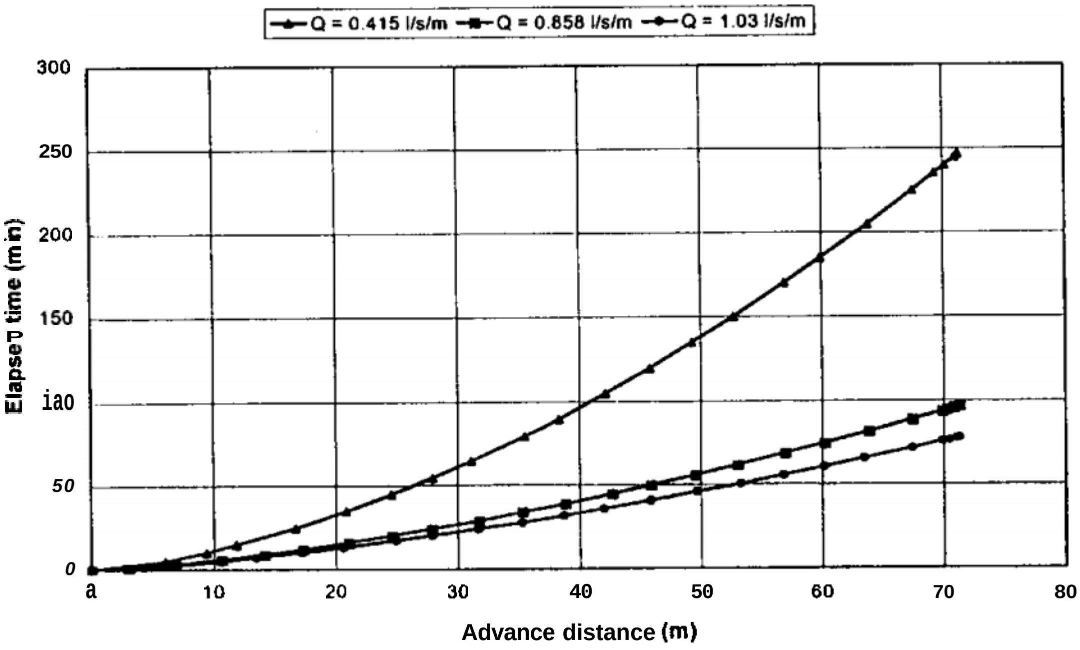


Figure 5.12. Simulated advance phase for selected discharges for the first irrigation event on Field 3 of Nawaz Farm.

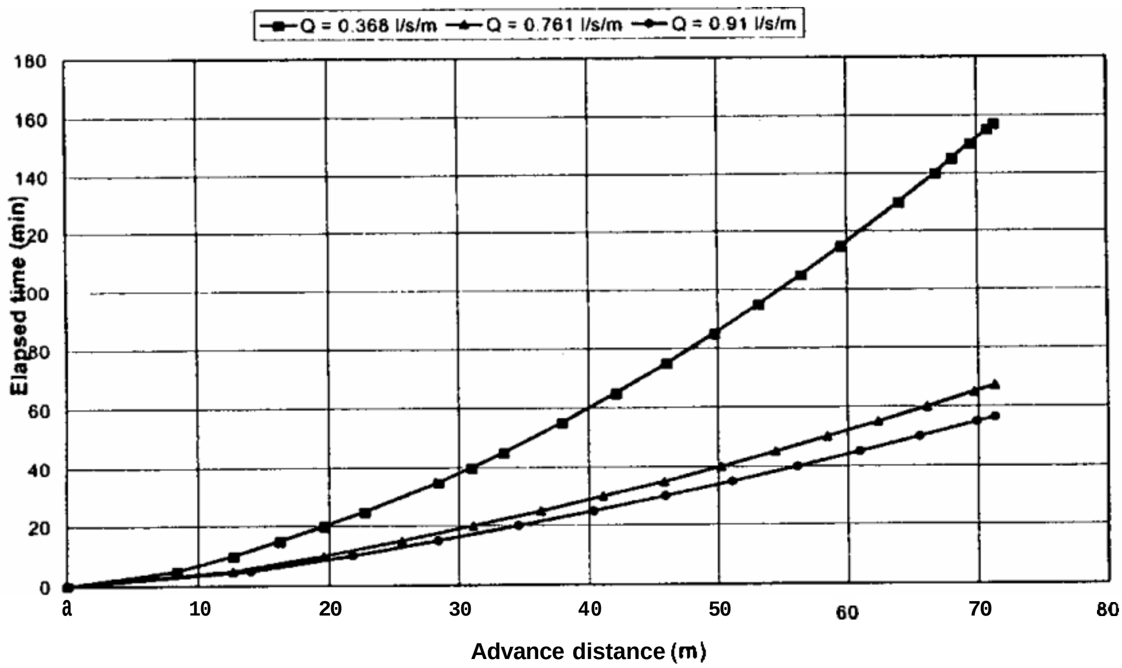


Figure 5.13. Simulated advance phase for selected discharges for the second irrigation event on Field 3 of Nawaz Farm.

For the under-irrigation cases concerning Field S4-6, Field 1 and Field 2, the farmer should irrigate longer than the actual advance time (with the exception of Event 1 on Field S4-6). Generally, in practice, farmers shut off the water when the water front is near the end of the field, or even more often they fix a certain time limit for irrigating one *kila*, despite the actual position of the water front. Overall, the irrigation performance does not improve significantly when only the cutoff time is modified for the actual applied discharge.

Table 5.5. Modified cutoff time for the present applied discharge for the selected irrigation events

	Date	t_{co} (min)	t_a (min)	E_a (%)	E_r (%)	DU (%)	Water Savings (%)	t_{red} (min)	t_{inc} (min)
Field S4-6									
Event 1	25/08/95	131 (127)	135.5	65.9	100	73.6	-		4
Event 2	12/09/95	83 (72)	75.2	77	100	83.5	-		11
Event 3	04/10/95	73 (45)	53.6	93.3	100	95.2	-		28
Field 1									
Event 1	14/01/96	78 (90)	69.9	58.1	100	72.6	7.8	22	
Event 2	06/02/96	52 (44)	43.3	83.3	100	87.9	-		8
Event 3	29/02/96	65 (61)	59.1	80.6	100	85.4	-		4
Event 4	12/03/96	48 (46)	47.3	85.3	100	89	-		2
Field 2									
Event 1	23/01/96	53 (78)	54.7	55.5	100	71.7	18	25	
Event 3	29/02/96	56 (55)	52.1	71.9	100	80.8	-		1
Event 4	12/03/96	49 (54)	45.6	79.5	100	86.1	7.3	5	
Event 5	28/03/96	25 (29)	30.4	51.5	100	71.1	10.4	4	
Field 3									
Event 1	19/01/96	292 (250)	246.6	76	100	89.5	-		42
Event 2	07/02/96	266 (164)	156.2	85.3	100	89.8	-		102
Event 3	02/03/96	192 (155)	142.2	90.6	100	92.7	-		37
Event 4	17/03/96	177 (147)	80.6	95.6	100	97.4	-		30

t_{red} = reduction in cutoff time ; t_{inc} = increase in cutoff time.

Although over-irrigation has been identified for the first irrigation on Field S4-6, due to the tail-end under irrigation. some application efficiency had to be sacrificed in order to achieve a 100% requirement efficiency. For the later irrigation events, under-irrigation is the predominant factor.

Field 3 faces a major problem due to the soil type, i.e. loam soil with an alkali crust. This crust layer delays the infiltration process. For this reason, the main problem lies with the irrigation duration. The farmer should irrigate much longer than the advance time. This will involve some sacrifice of the application efficiency, however, for the farmer it will be much more important to save his yield. Almost four acres of his land is of the same soil condition (alkali crust). Only about 1.5 acres is loam soil only (Sultanpur loam) and another one acre faces salinity throughout the profile (Jhakkar loam).

Modifying the field inflow per unit width along with the cutoff time

For Field S4-6, Field 1, Field 2 and Field 3, a higher inflow per unit width has been selected, corresponding with an acceptable reduced field width.

Tareen Farm

For Field S4-6, the field width, chosen for this exercise, corresponds to half of the original field width. Table 5.6 presents the results.

Field S4-6 W = 29.72 m	Date	Q (l/s/m)	Improved practice t_{co} (min)	E_a (%)	E_r (%)	Old practice E_a (%)	E_r (%)	Water savings (%)
Event 1	25/08/95	4.0062	53	74.5	100	61.3	99.6	13.2
Event 2	12/09/95	5.3066	37	87.7	100	86.3	97.1	1.4
Event 3	04/10/95	4.8428	37	93.3	100	99.3	65	

By improving the irrigation practices, a water saving is achieved for the first irrigation event, while a smaller water saving is achieved for the second irrigation event. Due to the large extent of under irrigation, as assessed for the third irrigation event, it is not water saving which has been achieved, but the under-irrigation has been eliminated by the improved practice. With respect to the irrigation duration (see also Table 5.1), the cutoff time should be close to the advance time in order to achieve a balanced irrigation.

Yasin farm

From Tables 5.2 and 5.3 for Field 1 and Field 2, respectively, can be derived that by reducing the field width along with modifying the cutoff time, water savings range between about 10% to 28.3% for the first irrigation on Field 1, about 13% - 18% for the first irrigation on Field 2; about 2% - 12% for the third irrigation on Field 2; and about 10% - 16% for the fourth irrigation on Field 2. With respect to the fifth irrigation on Field 2, the discharge had not been increased in the simulation, since the discharge was very high (3.2626 l/s/m), due to the canal water. Nevertheless, by adjusting the cutoff time, a water saving of about 6% had been achieved.

For the Fields 1 and 2 of Yasin Farm, the field width has been modified to 12 meters. A larger reduction would not be acceptable by the farmer, since too many bunded units would be difficult to manage. Table 5.7 presents the results on improved practices for the Fields 1 and 2. With respect to the under-irrigation cases, some application efficiency has to be sacrificed, however, this is very well compensated by the overall water savings. For the seven examined irrigation events, total water savings of 54% has been achieved for the two fields.

W = 12 m.	Date	Q (l/s/w)	t_{co} (min)	E_a (%)	E_r %)	E_a (%)	E_r (%)	Savings (%)
Event 1	14/01/96	1.65	46	68.2	100	50.3	100	17.9
Event 2	06/02/96	1.871	34	88.3	100	94.9	96	
Event 3	29/02/96	1.649	42	86.4	100	85.3	99.2	1.1
Event 4	12/03/96	1.734	32	88.7	100	88.8	99.6	
Field 2								
Event I	23/01/96	2.158	41	60.5	100	37.5	100	23
Event 3	29/02/96	1.908	45	75.4	100	73.2	99.9	2.2
Event 4	12/03/96	1.884	40	182.1	100	72	100	10.1

To provide an indication of the impact when extrapolated to the farm level, the improved performance for Fields 1 and 2, as presented in Tables 5.2 and 5.3, respectively, have been extrapolated to farm level through simulation, which concerns the sample fields, presented in Table 4.3. For this exercise, the discharge for each field has been adjusted by calculating the inflow per unit width for a field width of 12 meters. The results are presented in Table 5.8.

Yasin Farm W = 12 m.	improved Q l/s/m	Practice E_a (%)	E_r (%)	Old DU (%)	Practice E_a (%)	E_r (%)	Water Savings (%)
Event 1							
Bunded unit 01	1.7054	62.1	100	76.3	47	100	15.1
Bunded unit 34	2.0205	59.4	100	74.3	47.0	100	11.6
Bunded unit 35	2.0232	59.3	100	74	41.7	100	17.6
Bunded unit 36	1.989	60.3	100	73.3	51.3	100	9
Bunded unit 37	1.953	60	100	72.9	47.1	100	12.9
Bunded unit 38	2.0253	59.2	100	73.9	42.4	100	16.8
Bunded unit 39	2.0267	59.2	100	74.6	37	100	22.2
(Bundedunit41	2.3078	168.4	100	(78.6	(42.3	100	26.1
Event 2							
Bunded unit 09	1.891	87.3	100	91.1	85.9	100	1.4
Bunded unit 05	1.8493	86.7	100	91.5	96.8	96	
Bunded unit 06	1.8618	86.1	100	91.2	94.8	96.6	
Bunded unit 08	1 9058	189.3	100	91 4	100	92.5	

water savings are considerable, ranging between 1.4% - 26.1%, with 14.74% as an average. In terms of the under-irrigation cases, some of the application efficiency has been sacrificed.

Considering the whole farm. there is indeed potential for improving the irrigation practices, which evolve into a big impact in terms of water savings for the cases of over-irrigation. Furthermore, the simulated improved practices result in mitigating the under-irrigation, which will have a positive impact on the yield.

Once canal water is used, the discharge can go up till twice the current discharge. In this case, the farmer can irrigate two bunded units at the same time. However, since during the rabi irrigation season, the farmer depends.more on the tubewell water, it is more logical to design the fields for tubewell water use for this season.

With respect to irrigation duration, the simulation reveals that for the first irrigation, the cutoff time equals the advance time, while for the later irrigation events, the simulations reveal that the cutoff time slightly exceeds the advance time

Nawar Farm

Farmer Nawaz does not face problems in terms of over-irrigating his field, but under-irrigates the field. The average field inflow, as indicated for Field 3, does not exceed 0.5 l/s/m, which is quite low for a basin irrigation system, which results in long irrigation durations. The farmer has the tendency to irrigate longer than the advance time; however, not long enough to meet the crop water requirement at the tail end of the field. This, as indicated before, is related to the relatively low infiltration rates due to the alkali crust.

For this exercise, the inflow per unit width has been doubled (i.e. field width has been reduced to 30 meters). A larger field reduction is not considered, knowing the preference of the farmer for relatively larger fields. Table 5.9 presents the impact on irrigation performance by the proposed improved practices.

Field 3 W = 30 m.	Date	Q (l/s/m)	t_{co} (min)	t_a (min)	Improved E_a (%)	practice E_r (%)	Old E_a (%)	practice E_r (%)	Water savings (%)
Event 1	19/01/96	0.858	122	97	88.8	100	84.9	95.9	3.9
Event 2	07/02/96	0.761	121	67.2	91.1	100	99.9	72.1	
Event 3	02/03/96	0.786	95	68.8	92.1	100	100	89.5	
Event 4	17/03/96	0.896	86	47.6	99	100	100	87.3	

The results reveal that, for the first irrigation event, water savings can be obtained and the under-irrigation has been eliminated. For the remaining events, some application efficiency has to be sacrificed, however, for the farmer it is important that his yield is saved, which is the case when improved practices are considered.

Furthermore, with respect to irrigation duration, it is evident that the farmer should extend the irrigation duration up to 1.5 - 2 times the advance time, which is due to the low infiltration behavior of the **soil.**

Implications of improved practices on the total volume of water applied

Table 5.10 summarizes the total volume of water applied for the Fields S4-6, **1,** 2, and 3, that

Table 5.10. Total volume of water applied for the different improved scenarios, along with the original volume of water applied for the Fields S4-6, 1 2 and 3.

		Modified Q and t_{co}			**Modified t_{co} only**			**Old practice**		
	Date	**Q (l/s/m)**	**t_{co} (min)**	**Volume (m^3/m)**	**Q (l/s/m)**	**t_{co} (min)**	**Volume (m^3/m)**	**Q (l/s/m)**	**T_{co} (min)**	**Volume (m^3/m)**
Field S4-6										
Event 1	25/08/95	4.0062	53	12.74	2.0031	131	15.74	2.0031	127	15.26
Event 2	12/09/95	5.3066	37	11.78	2.6533	83	13.21	2.6533	72	11.46
Event 3	04/10/95	4.8428	37	10.75	2.4214	73	10.61	2.4214	45	6.54
Total volume of **water Applied** ***(m^3/m):***							39.56			33.26
Field 1										
Event 1	14/01/96	1.65	46	4.55	1.1315	78	5.30	1.1315	90	6.11
Event 2	06/02/96	1.871	34	3.82	1.283	52	4.00	1.283	44	3.39
Event 3	29/02/96	1.649	42	4.16	1.131	65	4.41	1.131	61	4.14
Event 4	12/03/96	1.734	32	3.33	1.1892	48	3.42	1.1892	**46**	3.28
Total volume of **water applied** ***(m^3/m):***										16.92
Field 2										
Event 1	23/01/96	2.158	41	5.31	1.8111	53	5.76	1.8111	78	8.48
Event 2	29/02/96	1.908	45	5.15	1.6013	56	5.38	1.6013	55	5.28
Event 3	12/03/96	1.884	40	4.52	1.581	49	4.65	1.581	54	5.12
Total volume of **water applied** ***(m^3/m):***										18.88
Field 3										
Event 1	19/01/96	0.858	122	6.28	0.4148	292	7.27	0.4148	250	6.22
Event2	07/02/96	0.761	121	5.52	0.368	266	5.87	0.368	164	3.62
Event3	02/03/96	0.786	95	4.48	0.3796	192	4.37	0.3796	155	3.53
Event4	17/03/96	0.896	86	4.62	0.4331	177	4.60	0.4331	147	3.82
Total volume of **water applied** ***(m^3/m):***				20.91			22.11			17.19

were examined for two scenarios (*i.e*. modifying cutoff time only and modifying the discharge and cutoff time) and the original performed practices.

Evidently, the water savings are "relative" when considered in comparison with the original performed practices, since these practices involve cases of under-irrigation, and, thus. application efficiency has to be sacrificed in order to meet the crop water requirement (i.e. Z_{req}). Only for Field 2, the total volume of water applied per unit width reduces considerably when the design variable are modified (Q and 1, as well as t_{co} only), since for this field, overall over-irrigation occurred for the selected irrigation events without any form of under-irrigation.

However, when the scenario on modifying the design variables, Q and t_{co} , is compared with the scenario when only the cutoff time, t_{co} is modified, differences can be observed in terms of volume of water applied per unit width. Taken the whole field into account, the overall implications for improved practices are considerable in terms of water savings.

By comparing the different fields, the improved practices have an overall larger impact on Field S4-6 as compared with the Fields 1, 2 and 3 in terms of the total volume of water applied per unit width. This has been identified earlier in this chapter. and can be ascribed to !he better soil surface condition (which has an impact on the infiltration behavior and consequently the irrigation performance) of Field S4-6 due to the laser leveling and the better maintenance practices during the season. Basically, laser-controlled land leveling[9] makes better uniform flow possible. The advance flow is not hindered as much because of less irregularities in the field micro topography. In other words, the laser-controlled land leveling facilitates the advance phase and consequently the uniformity. The advance phase is an important part of surface irrigation because it effects uniformity. About laser-controlled leveling, local irrigators in the United States stated that the single most important water management practice they can employ is "lasering" (personal communication with Dr. W.R. Walker).

[9] Laser-controlled land leveling was introduced to the Delta area of central Utah in 1980 by the USDA-ARS, U.S. Water Conservation Laboratory and Ihe Utah Agricultural Extension Service. Tests revealed that yield of wheat and barley were increased by more than 50%. presumeiy due to more uniform irrigation events (personal communication with Dr. W.R. Walker).

CHAPTER VI CONCLUSIONS

With reference to the main objective and the goals of this research, the following can be concluded:

- Assessment of the field irrigation performance

The simulated irrigation performance assessment reveals that for two-thirds of the monitored irrigation events, the irrigation turns out to be either insufficient or excessive. In only two instances a balanced irrigation has only been assessed. The first irrigation events deal mostly with over-irrigation. Complete under-irrigation, part of-the-field, or tail end under-irrigation mostly occurred for the later irrigation events. Furthermore, in quite some instances, the soil moisture distribution turned out to be unsatisfactory.

℘ Overall, the computer *irrigation* simulations reveal *that,* in most *of the* cases, *the* irrigation is unsatisfactorily performed and does not meet the actual crop wafer requirement.

The identified unsatisfactory irrigation performance has implications for the crop yield. which is reflected in the collected yield data for wheat. The results shows a declining tendency in yield for either cases of frequent over-irrigation (crop yield reduction in the head reach of the field) or for cases of frequent under-irrigation (crop yield reduction in the tail reach of the field).

p By *comparing* the results of the performance assessment and the yield data at the head, middle and tail of the field, a clear relationship exists between irrigation performance and the crop yield.

For the Yasin Farm, additional fields have been assessed, based on the prior derived infiltration functions. Due lo similar field conditions and the same trend in irrigation practices, the calibrated infiltration function, as derived for the Fields 1 and 2, could be satisfactorily extrapolated to other fields of the same farm. For most of the fields, the first irrigation also resulted in over-irrigation, which also has been the case for several fields during the second irrigation events. Some of the fields showed a tendency of under-irrigation for the second irrigation event.

℘ The evaluation of selected fields provided an insight into the overall on-farm irrigation performance. Overall, the identified unsatisfactory irrigation *performance* occurs at the field level for the entire farm.

- Optimization and management options

The discharge – application efficiency relationship has been derived through simulation. The results reveal that the application efficiency increases by increasing the discharge. Since there is no tail water problem with basins, the maximum unit inflow maximized the application efficiency. Additionally, it has been proven through the simulations that by increasing the discharge the advance time reduces. These two phenomena are of importance when its comes to improving the irrigation practices. Two scenarios have been tested: (i) impact of modifying the cutoff time on the irrigation performance; and (ii) impact of modifying the applied discharge and the cutoff time on the irrigation performance. In the over-irrigation cases, water savings could be achieved by modifying the cutoff time, whereas in the under-irrigation cases, some application efficiency has to be sacrificed in order to obtain a requirement efficiency of 100%. Modifying the applied discharge, as well as cutoff time, leads to a better irrigation performance and the overall water savings are considerable.

- An increase in irrigation performance is achieved by modifying the cutoff time and inflow per unit width. Improved practices have a positive impact on the water use in terms of water savings.

- Applicability **of the** hydrodynamic model

Model verification has been accomplished by comparing the simulated advance phase with the monitored advance phase. Results show that the advance phase is satisfactory simulated, however, some differences between monitored and predicted advance occurred, but field data extrapolation may have its impact too. Instability in the model has been encountered for the Fields **1** and 2. This might be ascribed to the irregular soil surface condition, which causes difficulties in the interpretation of the monitored advance data and deriving the advance function.

Overall, the application of the model has been experienced as being successful. Also, it proved to be a powerful and time-saving tool for developing improved scenarios and to develop relationships between the design variables and physical processes.

Potential for improved irrigation practices has been examined and quantified. However, for the farmer, it is difficult lo know how much water to apply in order to meet the exact crop water requirement. This, because a farmer does not know how much water he actually receives and what is the actual crop water requirement. Additionally, practicing irrigation is not an easy **job** and requires a lot **of** precision, knowledge and experience. Field **S4-6** of Tareen Farm is a good example. Although this farm has laser-controlled land leveling, a neutron probe for assessing the crop water requirement, and discharge measurement devices, balanced irrigation events have not been accomplished. However, better irrigation performance can be achieved on Field S4-6 of Tareen Farm as compared with the Fields **1,** 2 and **3** which are operated by farmers having less means (i.e. machinery and information on discharge and crop water requirement) at their disposal. Laser-controlled land leveling has a great impact on the irrigation performance, especially on the soil moisture distribution. Water is not only more economically used, moreover, a better yield can be achieved.

Another factor, which has an impact on the irrigation performance, is the soil type and soil quality. For lighter soils, it is more difficult to obtain higher application efficiencies as compared to heavier soils. When there is a salinity crust, the fact of very low infiltration behavior has to be taken into account in order to avoid under-irrigation.

Further research is being conducted in order to address feasible operation and management techniques for the farmers in order to improve the field and farm irrigation performance for basin irrigation systems in order to achieve water savings as well as better crop yields. Furthermore. research is being carried out on the use of bed-and-furrow irrigation systems, along with developing operation and management strategies. With this latter irrigation method, water can be saved, and, moreover, it provides for many crops a better growing environment. These are crucial components of development when a sustainable irrigated agriculture in Pakistan has to be achieved.

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ANNEX 1 COMPUTER SIMULATION OUTPUT FILE FOR SELECTED IRRIGATION EVENTS ON FIELD **S4-6** OF THE **TAREEN** FARM, **KHARIF** 1995 IRRIGATION SEASON.

FIELD S4-6 EVENT 7

************ HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 2.0031 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.050 Field Length, m = 147.8
Kost.-Lewis k, m**3/min**a/m = 0.00658
a = 0.5376 fo, m**3/min/m = 0.000067
Time Step in minutes = 1.0 Time of Cutoff, minutes = 127.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ. m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMAI*A**GAMA2

Section Parameter. ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	198.0	0.12481	0.12481
1	5.7	1.0	198.0	0.12588	0.12588
2	10.0	2.0	198.0	0.12551	0.12551
3	12.9	3.0	198.0	0.12513	0.12513
4	15.4	4.0	199.0	0.12476	0.12476
5	17.8	5.0	198.0	0.12438	0.12438
6	20.1	6.0	198.0	0.12400	0.12400
7	22.3	7.0	198.0	0.12362	0.12362
8	24.5	8.0	198.0	0.12324	0.12324
9	26.5	9.0	198.0	0.12286	0.12286
10	28.5	10.0	198.0	0.12248	0.12248
11	30.4	11.0	198.0	0.12210	0.12210
12	32.2	12.0	198.0	0.12172	0.12172
13	35.8	14.0	198.0	0.12095	0.12095
14	37.4	15.0	198.0	0.12057	0.12057
15	39.1	16.0	198.0	0.12018	0.12018

16	40.7	17.0	198.0	0.11979	0.11979
17	43.9	19.0	198.0	0.11902	0.11902
18	45.4	20.0	197.0	0.11824	0.11824
19	46.9	21.0	197.0	0.11785	0.11785
20	49.8	23.0	197.0	0.11707	0.11707
21	51.2	24.0	197.0	0.11667	0.11667
22	53.9	26.0	197.0	0.11588	0.11588
23	55.3	27.0	197.0	0.11549	0.11549
24	57.9	29.0	197.0	0.11469	0.11469
25	59.2	30.0	196.0	0.11390	0.11390
26	61.7	32.0	196.0	0.11310	0.11310
27	62.9	33.0	196.0	0.11269	0.11269
28	65.3	35.0	196.0	0.11189	0.11189
29	67.7	37.0	196.0	0.11108	0.11108
30	70.0	39.0	195.0	0.10985	0.10985
31	71.1	40.0	195.0	0.10944	0.10944
32	73.3	42.0	195.0	0.10862	0.10862
33	75.5	44.0	195.0	0.10779	0.10779
34	77.6	46.0	194.0	0.10654	0.10654
35	79.7	48.0	194.0	0.10570	0.10570
36	81.8	50.0	194.0	0.10486	0.10486
37	83.8	52.0	194.0	0.10401	0.10401
38	85.8	54.0	193.0	0.10273	0.10273
39	87.7	56.0	193.0	0.10187	0.10187
40	89.6	58.0	193.0	0.10101	0.10101
41	91.5	60.0	192.0	0.09971	0.09971
42	93.4	62.0	192.0	0.09883	0.09883
43	95.2	64.0	192.0	0.09795	0.09795
44	97.9	67.0	191.0	0.09617	0.09617
45	99.6	69.0	191.0	0.09527	0.09527
46	101.4	71.0	191.0	0.09436	0.09436
47	103.9	74.0	190.0	0.09254	0.09254
48	105.6	76.0	189.0	0.09115	0.09115
49	107.2	78.0	189.0	0.09022	0.09022
50	109.7	81.0	189.0	0.08881	0.08881
51	111.3	83.0	189.0	0.08786	0.08786
52	113.6	86.0	188.0	0.08593	0.08593
53	116.0	89.0	188.0	0.08447	0.08447
54	117.5	91.0	187.0	0.08300	0.08300
55	119.8	94.0	187.0	0.08150	0.08150
56	122.0	97.0	186.0	0.07947	0.07947
57	123.4	99.0	186.0	0.07845	0.07845
58	125.6	102.0	185.0	0.07636	0.07636
59	127.7	105.0	185.0	0.07478	0.07478
60	129.8	108.0	184.0	0.07262	0.07262
61	131.9	111.0	184.0	0.07097	0.07097
62	134.0	114.0	184.0	0.06930	0.06930
63	136.0	117.0	183.0	0.06702	0.06702
64	138.0	120.0	183.0	0.06527	0.06527
65	139.9	123.0	183.0	0.06349	0.06349
66	141.8	126.0	182.0	0.06106	0.06106

67	143.8	129.0	182.0	0.05918	0.05918
68	145.7	132.0	182.0	0.05727	0.05727
69	146.3	133.0	182.0	0.05662	0.05662
70	146.9	134.0	182.0	0.05596	0.05596
71	147.5	135.0	182.0	0.05530	0.05530
72	147.8	135.6	182.0	0.05344	0.05344

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z **for** a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance
Total Inflow = 15.143 m**3
Total Infilt = 15.174 m**3
Total Runoff = 0.000 m**3

Error = 0.205 percent

Efficiency - Uniformity Analysis

Application Efficiency = 61.3 percent
Storage Efficiency = 99.6 percent
Distribution Uniformity = 70.8 percent

FIELD S4-6 EVENT 2

************ HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 2.6533 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.040 Field Length, m = 147.8
Kost.-Lewis k, m**3/min**a/m = 0.00418
a = 0.6110 fo, m**3/min/m = 0.000054
Time Step in minutes = 1.0 Time of Cutoff, minutes = 72.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.07
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter. GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2
Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	137.0	0.08936	0.08936
1	7.7	1.0	137.0	0.09138	0.09138
2	13.3	2.0	136.0	0.09051	0.09051
3	17.5	3.0	136.0	0.09008	0.09008
4	21.0	4.0	136.0	0.08964	0.08964
5	24.4	5.0	136.0	0.08921	0.08921
6	27.7	6.0	136.0	0.08877	0.08877
7	30.8	7.0	135.0	0.08789	0.08789
8	33.8	8.0	135.0	0.08745	0.08745
9	36.7	9.0	135.0	0.08701	0.08701
10	39.5	10.0	135.0	0.08656	0.08656
11	42.2	11.0	135.0	0.08612	0.08612
12	44.8	12.0	135.0	0.08567	0.08567
13	47.4	13.0	135.0	0.08523	0.08523
14	49.9	14.0	135.0	0.08478	0.08478
15	52.3	15.0	135.0	0.08433	0.08433
16	54.7	16.0	135.0	0.08388	0.08388
17	57.0	17.0	135.0	0.08342	0.08342
18	59.2	18.0	135.0	0.08297	0.08297
19	61.4	19.0	135.0	0.08252	0.08252
20	63.6	20.0	135.0	0.08206	0.08206
21	65.7	21.0	134.0	0.08114	0.08114
22	67.8	22.0	134.0	0.08068	0.08068
23	69.9	23.0	134.0	0.08022	0.08022
24	71.9	24.0	134.0	0.07976	0.07976
25	73.9	25.0	134.0	0.07929	0.07929
26	75.8	26.0	134.0	0.07883	0.07883
27	77.7	27.0	134.0	0.07836	0.07836
28	79.6	28.0	134.0	0.07789	0.07789
29	81.5	29.0	134.0	0.07742	0.07742
30	83.3	30.0	134.0	0.07695	0.07695
31	85.1	31.0	134.0	0.07647	0.07647
32	86.9	32.0	134.0	0.07600	0.07600
33	88.6	33.0	134.0	0.07552	0.07552
34	90.4	34.0	133.0	0.07456	0.07456
35	93.7	36.0	133.0	0.07359	0.07359
36	95.4	37.0	133.0	0.07311	0.07311
37	97.1	38.0	133.0	0.07262	0.07262
38	98.7	39.0	133.0	0.07213	0.07213
39	101.9	41.0	133.0	0.07115	0.07115
40	103.4	42.0	132.0	0.07016	0.07016
41	105.0	43.0	132.0	0.06966	0.06966
42	106.5	44.0	132.0	0.06916	0.06916
43	109.6	46.0	132.0	0.06815	0.06815
44	111.0	47.0	132.0	0.06765	0.06765
45	114.0	49.0	132.0	0.06663	0.06663
46	115.4	50.0	132.0	0.06612	0.06612

47	116.8	51.0	132.0	0.06560	0.06560
48	119.7	53.0	131.0	0.06404	0.06404
49	121.0	54.0	131.0	0.06352	0.06352
50	123.8	56.0	131.0	0.06247	0.06247
51	125.1	57.0	131.0	0.06193	0.06193
52	127.8	59.0	131.0	0.06086	0.06086
53	129.1	60.0	131.0	0.06033	0.06033
54	131.7	62.0	131.0	0.05924	0.05924
55	133.0	63.0	131.0	0.05869	0.05869
56	135.5	65.0	131.0	0.05759	0.05759
57	136.8	66.0	131.0	0.05703	0.05703
58	139.3	68.0	131.0	0.05591	0.05591
59	141.7	70.0	131.0	0.05478	0.05478
60	142.9	71.0	131.0	0.05421	0.05421
61	145.5	73.0	131.0	0.05306	0.05306
62	146.6	74.0	131.0	0.05248	0.05248
63	147.8	75.0	131.0	0.05189	0.05189
64	147.8	75.0	131.0	0.05180	0.05180

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. **TZ ≠ Z** for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ *is* the **sum** of the infiltrated volume of water for the completed cycles **.**

Volume Balance
Total Inflow = 11.303 m**3
Total Infilt = 11.347 m**3
Total Runoff = 0.000 m“3

Error = 0.388 percent

Efficiency - Uniformity Analysis

Application Efficiency = 86.3 percent
Storage Efficiency = 97.1 percent
Distribution Uniformity = 78.5 percent

***FIELD S4-6 EVENT* 3**

************* HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 2.4214 Field Slope, mIm = 0.0000
Manning's n Coefficient = 0.050 Field Length, rn = 147.8
Kost.-Lewis **k,** m**3/min**a/m = **0.001**71
a = 0.4910 ***fo,* m**3/min/m** = 0.000047
Time Step in minutes = 1.0 Time ***of*** Cutoff, minutes = 45.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.07
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where **A**2R**1.33** = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMAI*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	2706.7	0.04563	0.04563
1	7.3	1.0	2706.7	0.04552	0.04552
2	12.9	2.0	2706.7	0.04541	0.04541
3	17.3	3.0	2706.7	0.04530	0.04530
4	21.1	4.0	2706.7	0.04519	0.04519
5	24.7	5.0	2706.7	0.04508	0.04508
6	28.2	6.0	2706.7	0.04497	0.04497
7	31.6	7.0	2706.7	0.04486	0.04486
8	34.9	8.0	2706.7	0.04475	0.04475
9	38.1	9.0	2706.7	0.04464	0.04464
10	41.2	10.0	2706.7	0.04452	0.04452
11	44.3	11.0	2706.7	0.04441	0.04441
12	47.3	12.0	2706.7	0.04430	0.04430
13	50.3	13.0	2706.7	0.04419	0.04419
14	53.2	14.0	2706.7	0.04407	0.04407
15	56.1	15.0	2706.7	0.04396	0.04396
16	58.9	16.0	2706.7	0.04384	0.04384
17	61.7	17.0	2706.7	0.04373	0.04373
18	64.4	18.0	2706.7	0.04361	0.04361
19	67.2	19.0	2706.7	0.04350	0.04350
20	69.8	20.0	2706.7	0.04338	0.04338
21	72.5	21.0	2706.7	0.04326	0.04326
22	75.1	22.0	2706.7	0.04315	0.04315
23	77.7	23.0	2706.7	0.04303	0.04303
24	80.3	24.0	2706.7	0.04291	0.04291
25	82.8	25.0	2706.7	0.04279	0.04279
26	85.3	26.0	2706.7	0.04267	0.04267
27	87.8	27.0	2706.7	0.04255	0.04255
28	90.3	28.0	2706.7	0.04243	0.04243
29	92.7	29.0	2706.7	0.04231	0.04231
30	95.2	30.0	2706.7	0.04218	0.04218
31	97.6	31.0	2706.7	0.04206	0.04206
32	99.9	32.0	2706.7	0.04194	0.04194

33	102.3	33.0	2706.7	0.04181	0.04181
34	104.7	34.0	2706.7	0.04169	0.04169
35	107.0	35.0	2706.7	0.04156	0.04156
36	109.3	36.0	2706.7	0.04143	0.04143
37	111.6	37.0	2706.7	0.04130	0.04130
38	113.9	38.0	2706.7	0.04117	0.04117
39	116.2	39.0	2706.7	0.04104	0.04104
40	118.5	40.0	2706.7	0.04091	0.04091
41	120.7	41.0	2706.7	0.04078	0.04078
42	122.9	42.0	2706.7	0.04065	0.04065
43	125.1	43.0	2706.7	0.04051	0.04051
44	127.3	44.0	2706.7	0.04038	0.04038
45	129.9	45.0	2706.7	0.04024	0.04024
46	132.1	46.0	2706.7	0.04010	0.04010
47	134.3	47.0	2706.7	0.03996	0.03996
48	136.5	48.0	2706.7	0.03981	0.03981
49	138.6	49.0	2706.7	0.03967	0.03967
50	140.7	50.0	2706.7	0.03952	0.03952
51	142.8	51.0	2706.7	0.03937	0.03937
52	144.9	52.0	2706.7	0.03922	0.03922
53	146.9	53.0	2706.7	0.03907	0.03907
54	147.8	53.5	2720.0	0.03864	0.03864

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 6.392 m**3
Total Infilt = 6.347 m**3
Total Runoff = 0.000 m**3

Error = 0.716 percent

Efficiency - Uniformity Analysis

Application Efficiency = 99.3 percent
Storage Efficiency = 65.0 percent
Distribution Uniformity = 93.6 percent

ANNEX 2 COMPUTER SIMULATION OUTPUT FILE FOR SELECTED IRRIGATION EVENTS ON FIELD 1 OF THE YASIN FARM, RABI *1995 - 1996* IRRIGATION SEASON.

FIELD 7, *EVENT* 7

************ HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 1.1315 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.080 Field Length, m = 58.4
Kost.-Lewis k, m**3/min**a/m = 0.00840
a = 0.4931 fo. m**3/min/m = 0.000193
Time Step in minutes = 1.0 Time of Cutoff, minutes = 90.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.05
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	138.0	0.12075	0.12075
1	3.3	1.0	138.0	0.12116	0.12116
2	7.6	3.0	138.0	0.12008	0.12008
3	11.6	6.0	138.0	0.11846	0.11846
4	14.1	8.0	138.0	0.11737	0.11737
5	17.3	11.0	138.0	0.11606	0.11606
6	20.3	14.0	137.0	0.11386	0.11386
7	23.0	17.0	137.0	0.11219	0.11219
8	25.5	20.0	137.0	0.11050	0.11050
9	28.6	24.0	137.0	0.10824	0.10824
10	31.5	28.0	137.0	0.10594	0.10594
11	34.9	33.0	136.0	0.10245	0.10245
12	37.4	37.0	136.0	0.10008	0.10008
13	40.4	42.0	136.0	0.09707	0.09707
14	43.7	48.0	136.0	0.09339	0.09339
15	46.3	53.0	135.0	0.08961	0.08961

16	49.3	59.0	135.0	0.08574	0.08574
17	52.6	66.0	135.0	0.08108	0.08108
18	55.2	72.0	135.0	0.07695	0.07695
19	57.3	77.0	135.0	0.07340	0.07340
20	57.7	78.0	135.0	0.07267	0.07267
21	58.1	79.0	135.0	0.07195	0.07195
22	58.4	79.6	135.0	0.06944	0.06944

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance
Total Inflow = 6.042 m**3
Total Infilt = 6.078 m**3
Total Runoff = 0.000 m**3

Error = 0.586 percent

Efficiency - Uniformity Analysis

Application Efficiency = 50.3 percent
Storage Efficiency = 100.0 percent
Distribution Uniformity = 79.6 percent

***FIELD* 7, *EVENT* 2**
************ HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 1.2830 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.070 Field Length, m = 58.4
Kost.-Lewis k, m**3/min**a/m = 0.00477
a = 0.5151 fo, m**3/min/m = 0.000174
Time Step in minutes = 1.0 Time of Cutoff, minutes = 44.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ. m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	143.8	0.06499	0.06499
1	4.2	1.0	145.3	0.06442	0.06442
2	7.6	2.0	145.3	'0.06459	0.06459
3	9.9	3.0	145.3	0.06413	0.06413
4	13.6	5.0	145.3	0.06323	0.06323
5	17.1	7.0	145.3	0.06231	0.06231
6	20.4	9.0	145.3	0.06139	0.06139
7	21.9	10.0	145.3	0.06093	0.06093
8	26.3	13.0	145.3	0.05991	0.05991
9	29.0	15.0	143.8	0.05833	0.05833
10	31.5	17.0	143.8	0.05738	0.05738
11	34.0	19.0	143.8.	0.05642	0.05642
12	37.5	22.0	143.8	0.05496	0.05496
13	39.8	24.0	143.8	0.05398	0.05398
14	43.0	27.0	143.8	0.05249	0.05249
15	46.1	30.0	143.8	0.05098	0.05098
16	49.1	33.0	143.8	0.04945	0.04945
17	51.9	36.0	143.8	0.04789	0.04789
18	54.7	39.0	143.8	0.04630	0.04630
19	56.4	41.0	143.8	0.04522	0.04522
20	57.3	42.0	143.8	0.04468	0.04468
21	58.2	43.0	143.8	0.04413	0.04413
22	58.4	43.2	143.8	0.04352	0.04352

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 3.310 m**3
Total Infilt = 3.340 m**3
Total Runoff = 0.000 m**3

Error = 0.887 percent

Efficiency - Uniformity Analysis

Application Efficiency = 94.9 percent
Storage Efficiency = 96.0 percent
Distribution Uniformity = 84.4 percent

FIELD 1, EVENT 3
************ HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 1.1310 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.080 Field Length, m = 58.4
Kost.-Lewis k, m**3/min**a/m = 0.00711
a = 0.4571 fo, m**3/min/m = 0.000152
Time Step in minutes = 1.0 Time of Cutoff, minutes = 61.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	146.2	0.07977	0.07977
1	3.5	1.0	146.2	0.08000	0.08000
2	8.1	3.0	146.2	0.07920	0.07920
3	11.1	5.0	146.2	0.07839	0.07839
4	14.0	7.0	146.2	0.07758	0.07758
5	16.6	9.0	146.2	0.07677	0.07677
6	20.2	12.0	146.2	0.07553	0.07553
7	22.5	14.0	146.2	0.07470	0.07470
8	25.7	17.0	146.2	0.07374	0.07374
9	28.7	20.0	145.0	0.07199	0.07199
10	31.5	23.0	145.0	0.07071	0.07071
11	34.2	26.0	145.0	0.06941	0.06941
12	37.6	30.0	145.0	0.06765	0.06765
13	40.9	34.0	143.8	0.06536	0.06536
14	43.2	37.0	143.8	0.06400	0.06400
15	46.2	41.0	143.8	0.06215	0.06215
16	49.1	45.0	143.8	0.06027	0.06027
17	52.5	50.0	143.8	0.05785	0.05785
18	55.2	54.0	143.8	0.05587	0.05587
19	57.1	57.0	143.8	0.05435	0.05435
20	57.7	58.0	143.8	0.05383	0.05383

21	58.3	59.0	143.8	0.05332	0.05332
22	58.4	59.1	143.8	0.05292	0.05292

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles

Volume Balance

Total Inflow = 4.072 m**3
Total Infilt = 4.098 m**3
Total Runoff = 0.000 m**3

Error = 0.638 percent

Efficiency - Uniformity Analysis

Application Efficiency = 85.3 percent
Storage Efficiency = 99.2 percent
Distribution Uniformity = 83.8 percent

FIELD 1, EVENT 4

************ HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 1.1892 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.090 Field Length, m = 58.4
Kost.-Lewis k, m**3/min**a/m = 0.00565
a = 0.4260 fo, m**3/min/m = 0.000151
Time Step in minutes = 1.0 Time of Cutoff, minutes = 46.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.05
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	232.4	0.06141	0.06141
1	3.6	1.0	232.4	0.06110	0.06110
2	8.7	3.0	232.4	0.06049	0.06049
3	10.3	4.0	234.4	0.06008	0.06008
4	13.6	6.0	234.4	0.05996	0.05996
5	16.6	8.0	234.4	0.05933	0.05933
6	19.5	10.0	234.4	0.05871	0.05871
7	22.2	12.0	234.4	0.05808	0.05808
8	26.1	15.0	234.4	0.05743	0.05743
9	28.5	17.0	232.4	0.05628	0.05628
10	32.0	20.0	232.4	0.05531	0.05531
11	34.2	22.0	232.4	0.05466	0.05466
12	37.4	25.0	232.4	0.05368	0.05368
13	40.6	28.0	232.4	0.05269	0.05269
14	43.6	31.0	232.4	0.05168	0.05168
15	46.5	34.0	232.4	0.05067	0.05067
16	49.3	37.0	232.4	0.04964	0.04964
17	52.0	40.0	232.4	0.04860	0.04860
18	54.7	43.0	232.4	0.04755	0.04755
19	56.4	45.0	232.4	0.04684	0.04684
20	57.4	46.0	232.4	0.04648	0.04648
21	58.2	47.0	232.4	0.04612	0.04612
22	58.4	47.2	232.4	0.04535	0.04535

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ $\neq$ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 3.211 m**3
Total Infilt = 3.235 m”3
Total Runoff = 0.000 m**3

Error = 0.753 percent

Efficiency - Uniformity Analysis

Application Efficiency = 88.8 percent
Storage Efficiency = 99.6 percent
Distribution Uniformity = 88.2 percent

ANNEX 3 COMPUTER SIMULATION OUTPUT FILE FOR SELECTED IRRIGATION EVENTS ON FIELD 2 OF THE YASIN FARM, RABI 1995 - 1996 IRRIGATION SEASON.

FIELD 2, EVENT 1

************ HYDRODYNAMIC MODEL ***********

```
Inflow, lps/s/m or furrow    = 1.6190    Field Slope, m/m         = 0.0000
Manning's n Coefficient   = 0.080    Field Length, m          =   60.3
Kost.-Lewis k, m**3/min**a/m  = 0.00781
             a        = 0.5810    fo. m**3/mln/m          = 0.000174
Time Step in minutes     =    1.0    Time of Cutoff, minutes  =   63.0
Space Weight Factor, PHI  =   0.60    Time Weight Factor, THETA  =   0.60
Application Depth, ZREQ, m =   0.05
Section Parameter, RHO1   =  1.000    RHO2                    =  3.333
   where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1  =  1.000    SIGMA2                  =  1.000
   where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1  =  1.000    GAMA2                   =  0.000
   where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1  =  1.000    ZETA2                   =  0.000
   where T = ZETA1*Y**ZETA2

Downstream Boundary  ALPHB =  0.0000    AMPB                  = 1.4000
   where Qout = ALPHB*A**AMPB
```

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	92.0	0.12206	0.12206
1	4.2	1.0	92.0	0.12268	0.12268
2	7.6	2.0	92.0	0.12182	0.12182
3	11.3	4.0	92.0	0.12008	0.12008
4	14.6	6.0	92.0	0.11833	0.11833
5	17.6	8.0	92.0	0.11710	0.11710
6	20.2	10.0	92.0	0.11533	0.11533
7	23.9	13.0	92.0	0.11264	0.11264
8	26.1	15.0	92.0	0.11083	0.11083
9	29.2	18.0	92.0	0.10808	0.10808
10	32.9	22.0	91.0	0.10342	0.10342
11	35.5	25.0	91.0	0.10057	0.10057
12	38.7	29.0	90.0	0.09571	0.09571
13	41.7	33.0	90.0	0.09173	0.09173
14	45.2	38.0	89.0	0.08557	0.08557
15	47.8	42.0	88.0	0.08023	0.08023

16	50.8	47.0	07.0	0.07356	0.07356
17	54.2	53.0	87.0	0.06651	0.06651
18	56.8	58.0	87.0	0.06029	0.06029
19	58.9	62.0	87.0	0.05503	0.05503
20	59.4	63.0	87.0	0.05367	0.05367
21	59.9	64.0	87.0	0.05229	0.05229
22	60.3	64.9	87.0	0.04982	0.04902

x_a = advance distance; t_a = advance time; t_r = recession lime; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water **for** a particular cycle, and TZ is We **sum** of the infiltrated volume of water for the completed cycles .

Volume Balance
Total Inflow = 6.023 m**3
Total Infilt = 6.039 m**3
Total Runoff = 0.000 m**3

Error = 0.269 percent

Efficiency - Uniformity Analysis

Application Efficiency = 52.1 percent
Storage Efficiency = 100.0 percent
Distribution Uniformity = 69.2 percent

FIELD 2, EVENT 3

************ HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 1.6013 Field **Slope,** mlm = 0.0000
Manning's n Coefficient = 0.080 Field Length, m = 60.3
Kost.-Lewis k, m**3/min**a/m = 0.00681
a = 0.5623 fo, m**3/min/m = 0.000136
Time Step in minutes = 1.0 Time of Cutoff, minutes = 55.0
Space Weight Factor. PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter. SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	96.0	0.10007	0.10007
1	4.3	1.0	96.0	0.10067	0.10067
2	7.8	2.0	96.0	0.10001	0.10001
3	11.8	4.0	96.0	0.09869	0.09869
4	13.6	5.0	96.0	0.09802	0.09802
5	16.9	7.0	96.0	0.09667	0.09667
6	20.0	9.0	96.0	0.09573	0.09573
7	22.8	11.0	95.0	0.09368	0.09368
8	26.8	14.0	95.0	0.09161	0.09161
9	29.2	16.0	95.0	0.09021	0.09021
10	32.6	19.0	95.0	0.08809	0.08809
11	35.8	22.0	95.0	0.08594	0.08594
12	38.7	25.0	94.0	0.08303	0.08303
13	41.6	28.0	94.0	0.08080	0.08080
14	45.1	32.0	94.0	0.07778	0.07778
15	47.7	35.0	94.0	0.07546	0.07546
16	50.9	39.0	93.0	0.07151	0.07151
17	53.9	43.0	93.0	0.06824	0.06824
18	56.8	47.0	93.0	0.06489	0.06489
19	58.9	50.0	93.0	0.06230	0.06230
20	59.6	51.0	93.0	0.06142	0.06142
21	60.3	52.0	93.0	0.06053	0.06053
22	60.3	52.1	93.0	0.06032	0.06032

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 5.188 m**3
Total Infilt = 5.229 m**3
Total Runoff = 0.000 m**3

Error = 0.780 percent

Efficiency - Uniformity Analysis

Application Efficiency = 73.2 percent
Storage Efficiency = 99.9 percent
Distribution Uniformity = 80.3 percent

FIELD 2, EVENT 4

************* HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 1.5810 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.090 Field Length, m = 60.3
Kost.-Lewis k, m**3/min**a/m = 0.00587
a = 0.5395 fo. m**3/min/m = 0.000117
Time Step in minutes = 1.0 Time of Cutoff, minutes = 54.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	238.3	0.09286	0.09286
1	4.2	1.0	238.3	0.09196	0.09196
2	7.8	2.0	240.2	0.09222	0.09222
3	11.9	4.0	238.3	0.09129	0.09129
4	13.7	5.0	238.3	0.09082	0.09082
5	17.2	7.0	238.3	0.08987	0.08987
6	20.4	9.0	238.3	0.08892	0.08892
7	23.5	11.0	238.3	0.08796	0.08796
8	26.3	13.0	238.3	0.08700	0.08700
9	29.0	15.0	238.3	0.08603	0.08603
10	32.8	18.0	238.3	0.08456	0.08456
11	35.2	20.0	238.3	0.08358	0.08358
12	38.6	23.0	238.3	0.08209	0.08209
13	41.9	26.0	238.3	0.08058	0.08058
14	45.0	29.0	238.3	0.07905	0.07905
15	48.0	32.0	238.3	0.07751	0.07751
16	50.9	35.0	238.3	0.07595	0.07595
17	53.7	38.0	238.3	0.07436	0.07436
18	57.3	42.0	238.3	0.07222	0.07222
19	58.1	43.0	238.3	0.07168	0.07168
20	59.0	44.0	238.3	0.07113	0.07113

21	59.8	45.0	238.3	0.07059	0.07059
22	60.3	45.6	238.3	0.06909	0.06909

x_a = advance distance; t_a = advance time; t_r = recession time; **Z** = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and **TZ** is the sum of the infiltrated volume of waler for the completed cycles .

Volume Balance
Total Inflow = 5.028 m**3
Total Infilt = 5.083 m**3
Total Runoff = 0.000 m**3

Error = 1.108 percent

Efficiency - Uniformity Analysis

Application Efficiency = 72.0 percent
Storage Efficiency = 100.0 percent
Distribution Uniformity = 88.7 percent

FIELD 2, EVENTS

************ HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 3.2626 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.090 Field Length, m = 60.3
Kost.-Lewis k, m**3/min**a/m = 0.00780
a = 0.6340 fo, m**3/min/m = 0.000117
Time Step in minutes = 10 Time of Cutoff. rninutos = 29.0
Space Weight Factor, PHI = 0.60 Time Weight Faclor. THETA = 0.60
Application Depth, ZREQ, m = 0.04
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	59.0	0.10706	0.10706
1	5.9	1.0	59.0	0.10914	0.10914
2	10.9	2.0	58.0	0.10665	0.10665
3	14.2	3.0	58.0	0.10540	0.10540
4	16.7	4.0	58.0	0.10414	0.10414
5	19.2	5.0	58.0	0.10287	0.10287
6	23.9	7.0	57.0	0.09901	0.09901
7	26.1	8.0	57.0	0.09771	0.09771
8	28.2	9.0	57.0	0.09640	0.09640
9	32.1	11.0	57.0	0.09375	0.09375
10	35.8	13.0	57.0	0.09106	0.09106
11	37.6	14.0	57.0	0.08970	0.08970
12	40.9	16.0	57.0	0.08695	0.08695
13	44.1	18.0	56.0	0.08273	0.08273
14	47.1	20.0	56.0	0.07986	0.07986
15	50.0	22.0	56.0	0.07693	0.07693
16	54.1	25.0	56.0	0.07243	0.07243
17	56.8	27.0	56.0	0.06935	0.06935
18	58.0	28.0	56.0	0.06778	0.06778
19	59.4	29.0	56.0	0.06619	0.06619
20	60.3	29.7	56.0	0.06373	0.06373

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water; TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ $\neq$ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 5.481 m**3
Total Infilt = 5.585 m**3
Total Runoff = 0.000 m**3

Error = 1.890 percent

Efficiency - Uniformity Analysis

Application Efficiency = 45.1 percent
Storage Efficiency = 100.0 percent
Distribution Uniformity = 79.6 percent

ANNEX 4 COMPUTER SIMULATION OUTPUT FILE FOR SELECTED IRRIGATION EVENTS ON FIELD 3 OF THE NAWAZ FARM, RABI 1995 - 1996 IRRIGATION SEASON.

FIELD 3, EVENT 1

************ HYDRODYNAMIC MODEL ***********

Inflow. lps/s/m or furrow = 0.4148 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.080 Field Length, m = 71.3
Kost.-Lewis k, m**3/min**a/m = 0.00705
a = 0.4493 fo, m**3/min/m = 0.000016
Time Step in minutes = 1.0 Time of Cutoff, minutes = 250.0
Space Weight Factor. PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth. ZREQ. m = 0.08
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous **Flow** Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	345.0	0.10266	0.10266
1	3.4	2.0	345.0	0.10261	0.10261
2	6.6	6.0	344.0	0.10189	0.10189
3	10.4	12.0	343.0	0.10087	0.10087
4	14.1	19.0	342.0	0.09970	0.09970
5	17.8	27.0	341.0	0.09836	0.09836
6	21.0	35.0	340.0	0.09701	0.09701
7	24.7	45.0	339.0	0.09532	0.09532
8	28.4	56.0	338.0	0.09345	0.09345
9	31.9	67.0	338.0	0.09170	0.09170
10	35.6	80.0	337.0	0.08942	0.08942
11	39.1	93.0	336.0	0.08707	0.08707
12	42.7	107.0	335.0	0.08448	0.08448
13	46.3	122.0	334.0	0.08163	0.08163
14	49.7	137.0	333.0	0.07866	0.07866
15	53.4	154.0	332.0	0.07518	0.07518

16	56.9	171.0	331.0	0.07150	0.07150
17	60.5	189.0	331.0	0.06762	0.06762
18	64.1	208.0	330.0	0.06299	0.06299
19	67.7	228.0	329.0	0.05769	0.05769
20	70.8	246.0	329.0	0.05267	0.05267
21	71.0	247.0	329.0	0.05237	0.05237
22	71.2	248.0	329.0	0.05207	0.05207
23	71.3	248.8	329.0	0.04983	0.04983

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water **TZ** = *Z* for a continuous flow regime. **TZ** ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume **of** water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles.

Volume Balance
Total Inflow = 6.197 m**3
Total Infilt = 6.106 m**3
Total Runoff = 0.000 m**3

Error = 1.466 percent

Efficiency - Uniformity Analysis

Application Efficiency = 84.9 percent
Storage Efficiency = 95.9 percent
Distribution Uniformity = 75.2 percent

FIELD 3, EVENT 2

************* HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 0.3680 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.070 Field Length, m = 71.3
Kost.-Lewis k, m**3/min**a/m = 0.00252
a = 0.5511 fo, m**3/min/m = 0.000020
Time Step in minutes = 1.0 Time of Cutoff, minutes = 164.0
Space Weight Factor. PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ. m = 0.07
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMAl = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2
Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	261.0	0.05906	0.05906
1	2.5	1.0	263.0	0.05939	0.05939
2	6.7	4.0	263.0	0.05899	0.05899
3	10.7	8.0	263.0	0.05845	0.05845
4	14.1	12.0	263.0	0.05791	0.05791
5	17.1	16.0	264.0	0.05736	0.05736
6	21.2	22.0	263.0	0.05653	0.05653
7	24.9	28.0	262.0	0.05556	0.05556
8	28.2	34.0	261.0	0.05458	0.05458
9	31.9	41.0	260.0	0.05344	0.05344
10	35.2	48.0	259.0	0.05228	0.05228
11	39.2	57.0	258.0	0.05081	0.05081
12	42.5	65.0	257.0	0.04947	0.04947
13	46.0	74.0	256.0	0.04794	0.04794
14	49.7	84.0	255.0	0.04622	0.04622
15	53.1	94.0	255.0	0.04463	0.04463
16	56.7	105.0	255.0	0.04282	0.04282
17	60.4	117.0	255.0	0.04079	0.04079
18	63.9	129.0	255.0	0.03869	0.03869
19	67.6	142.0	254.0	0.03614	0.03614
20	70.7	154.0	254.0	0.03385	0.03385
21	71.0	155.0	254.0	0.03365	0.03365
22	71.2	156.0	254.0	0.03346	0.03346
23	71.3	156.2	254.0	0.03318	0.03318

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ $\neq$ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 3.599 m**3
Total Infilt = 3.588 m**3
Total Runoff = 0.000 m**3

Error = 0.294 percent

Efficiency - Uniformity Analysis

Application Efficiency = 99.7 percent
Storage Efficiency = 71.9 percent
Distribution Uniformity = 78.3 percent

FIELD 3, EVENT 3

************* HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 0.3796 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.080 Field Length, m = 71.3
Kost.-Lewis k, m**3/min**a/m = 0.00390
a = 0.4300 fo, m**3/min/m = 0.000019
Time Step in minutes = 1.0 Time of Cutoff, minutes = 155.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.05
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	822.8	0.05406	0.05406
1	2.2	1.0	822.8	0.05426	0.05426
2	6.9	5.0	822.8	0.05394	0.05394
3	10.5	9.0	822.8	0.05361	0.05361
4	13.6	13.0	822.8	0.05329	0.05329
5	17.8	19.0	825.2	0.05280	0.05280
6	21.0	24.0	822.8	0.05239	0.05239
7	24.6	30.0	822.8	0.05189	0.05189
8	28.5	37.0	822.8	0.05130	0.05130
9	31.6	43.0	822.8	0.05079	0.05079
10	35.6	51.0	820.3	0.04997	0.04997
11	38.9	58.0	817.9	0.04922	0.04922
12	42.5	66.0	817.9	0.04852	0.04852
13	46.0	74.0	817.9	0.04781	0.04781
14	49.8	83.0	817.9	0.04699	0.04699
15	53.4	92.0	815.4	0.04603	0.04603
16	56.8	101.0	815.4	0.04518	0.04518
17	60.6	111.0	815.4	0.04423	0.04423
18	64.2	121.0	815.4	0.04326	0.04326
19	67.7	131.0	815.4	0.04226	0.04226
20	70.4	139.0	815.4	0.04145	0.04145

21	70.7	140.0	815.4	0.04135	0.04135
22	71.1	141.0	815.4	0.04125	0.04125
23	71.3	141.7	815.4	0.04000	0.04000

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ ≠ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance
Total Inflow = 3.507 m**3
Total Infilt = 3.510 m**3
Total Runoff = 0.000 m**3

Error = 0.076 percent

Efficiency - Uniformity Analysis

Application Efficiency = 100.0 percent
Storage Efficiency = 89.5 percent
Distribution Uniformity = 88.6 percent

FIELD 3, EVENT 4

************* HYDRODYNAMIC MODEL ***********

Inflow, lps/s/m or furrow = 0.4331 Field Slope, m/m = 0.0000
Manning's n Coefficient = 0.090 Field Length, m = 71.3
Kost.-Lewis k, m**3/min**a/m = 0.00120
a = 0.4883 fo, m**3/min/m = 0.000017
Time Step in minutes = 1.0 Time of Cutoff, minutes = 147.0
Space Weight Factor, PHI = 0.60 Time Weight Factor, THETA = 0.60
Application Depth, ZREQ, m = 0.06
Section Parameter, RHO1 = 1.000 RHO2 = 3.333
where A**2R**1.33 = RHO1*A**RHO2

Section Parameter, SIGMA1 = 1.000 SIGMA2 = 1.000
where A = SIGMA1*Y**SIGMA2

Section Parameter, GAMA1 = 1.000 GAMA2 = 0.000
where WP = GAMA1*A**GAMA2

Section Parameter, ZETA1 = 1.000 ZETA2 = 0.000
where T = ZETA1*Y**ZETA2

Downstream Boundary ALPHB = 0.0000 AMPB = 1.4000
where Qout = ALPHB*A**AMPB

Continuous Flow Advance-Recession Trajectory

Node	x_a (m)	t_a (min)	t_r (min)	Z (m^3/m)	TZ (m^3/m)
0	0.0	0.0	4946.7	0.05516	0.05516
1	2.7	1.0	4946.7	0.05511	0.05511
2	6.4	3.0	4946.7	0.05500	0.05500
3	10.3	6.0	4946.7	0.05485	0.05485
4	13.9	9.0	4946.7	0.05469	0.05469
5	17.2	12.0	4946.7	0.05454	0.05454
6	21.4	16.0	4946.7	0.05432	0.05432
7	24.3	19.0	4946.7	0.05417	0.05417
8	28.1	23.0	4946.7	0.05395	0.05395
9	31.7	27.0	4946.7	0.05373	0.05373
10	35.1	31.0	4946.7	0.05352	0.05352
11	38.5	35.0	4946.7	0.05329	0.05329
12	42.5	40.0	4946.7	0.05301	0.05301
13	45.7	44.0	4946.7	0.05279	0.05279
14	49.5	49.0	4946.7	0.05250	0.05250
15	53.2	54.0	4946.7	0.05220	0.05220
16	56.8	59.0	4946.7	0.05190	0.05190
17	60.3	64.0	4946.7	0.05160	0.05160
18	63.8	69.0	4946.7	0.05129	0.05129
19	67.2	74.0	4946.7	0.05097	0.05097
20	69.8	78.0	4946.7	0.05070	0.05070
21	70.5	79.0	4946.7	0.05064	0.05064
22	71.1	80.0	4946.7	0.05057	0.05057
23	71.3	80.3	4960.0	0.05039	0.05039

x_a = advance distance; t_a = advance time; t_r = recession time; Z = infiltrated volume of water;TZ = infiltrated volume of water TZ = Z for a continuous flow regime. TZ $\neq$ Z for a surge flow regime (for each simulated cycle); then Z = infiltrated volume of water for a particular cycle, and TZ is the sum of the infiltrated volume of water for the completed cycles .

Volume Balance

Total Inflow = 3.794 m**3
Total Infilt = 3.799 m**3
Total Runoff = 0.000 m**3

Error = 0.142 percent

Efficiency - Uniformity Analysis

Application Efficiency = 100.0 percent
Storage Efficiency = 87.3 percent
Distribution Uniformity = 96.4 percent

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RESEARCH REPORTS

Report No.	Title	Author	Year
R-1	**Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan** Volume I: Synthesis of Findings and Recommendations	Carlos Garces-R D.J. Bandaragoda Pierre Strosser	June 1994
	Volume II: Research Approach and Interpretation	Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan	June 1994
	Volume III: Data Collection Procedures and Data Sets	Rana M. Alaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R	June 1994
R-2	Salinity and Sodicity Research in Pakistan - Proceedings of a one-day Workshop	J.W. Kijne Marcel Kuper Muhammad Aslam	Mar 1995
R-3	Farmers' Perceptions on Salinity and Sodicity: A case study into farmers' knowledge of salinity and sodicity, and their strategies and practices to deal with salinity and sodicity in their farming systems	Neeltje Kielen	May 1996
R-4	Modelling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level (M.Sc Thesis - published as Research Report)	S.M.P. Smets	June 1996
R-5	Water Distribution at the Secondary Level in the Chishtian.Sub-division	M. Amin K. Tareen Khalid Mahmood Anwar Iqbal Mushtaq Khan Marcel Kuper	July 1996
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R-21	**Salinity Management Alternatives for the Rechna Doab, Punjab, Pakistan**			
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